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OTA Report

Exploration for Strategic Materials

prepared by

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"These Working Papers were prepared by outside contractors as an input to an ongoing OTA Assessment. They do not necessarily reflect the analytical findings of OTA. These Working Papers have been neither reviewed nor approved by the Technology Assessment Board."

J952-56

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"This is an OTA Working Paper that was used in preparing OTA's final Assessment Report on Strategic Materials: Technologies to Reduce U.S. Import Vulnerability. OTA makes these Working Papers available for the use of readers desiring a more detailed or technical discussion of an issue than can normally be accommodated in our final Report. As an OTA Working Paper, this report has not been reviewed or approved by the Technology Assessment Board. The findings and conclusions expressed in the report are those of the authors and do not necessarily reflect the views of OTA, the Strategic Materials Advisory Panel, or the Technology Assessment Board."

Foreword

This report was prepared by DMEA Ltd., of Scottsdale, Arizona, under OTA Contract Number 333-5940.0, in support of the OTA assessment of technologies to reduce U.S. materials import vulnerability. The objectives of this study were to 1) identify and evaluate current exploration technology and methodology used in the search for non-fuel minerals and their applicability to the search for strategic materials; 2) identify potential developments in technology over the next 25 years which could lead to the discovery of additional deposits of strategic materials; and 3) describe the effects of non-technical factors on exploration today, and on development and implementation of technical innovations in exploration for strategic materials in the future.

For purposes of this report, OTA's definition of the strategic minerals considered is employed:

> "A strategic mineral is one for which the quantity required for essential military and civilian uses with no available economic substitutes exceeds the reasonably secure domestic and foreign sources of supply. Using this definition, OTA has identified four materials on which the U.S. is import dependent as "strategic": chromium, cobalt, manganese and platinum group metals."

This report is confined to discussion of technologies, methodologies and the effects of technical and non-technical factors on exploration for on-shore deposits of strategic materials.

Information for this study was gathered from published sources; from interviews with experts in genetic theory, exploration technology, exploration management; and from the authors' personal experience in such areas. The principal author, Ben F. Dickerson III, has over 32 years experience in the minerals exploration field.

Appendix E contains a list of the experts who were interviewed and who contributed their opinions on the subjects under study. The Appendix also contains A: Plate Tectonic Classification of Ore Deposits; B: Exploration Flow Chart - Example; C: Predictive Metallogeny: A Symposium; D: Precious Metals Exploration by James A. Anderson; and F: Lists of World Class Deposits discovered in the past 30 years.

Some readers of this report may think it pessimistic. We believe it to be realistic, a quite differing view.

It appears obvious to us that a major barrier shields the government's mineral policy makers and advisors from the true realities of the mineral exploration world.

In great part, this barrier appears to reflect a fundamental oversight of the basic purpose of mineral exploration - to make money in the near future, not 20 years hence.

Those who provide the basic scientific geologic expertise to the government are well qualified in their specialties and are worthy individuals. Nevertheless, most have a quite limited knowledge of pragmatic mineral exploration and the actual realities of the corporate explorers' day-to-day work. Few, if any, of the government's in-house advisors have had the responsible control of exploration funds. Such responsibility engenders and requires a quite differing view of the practical value assigned to geologic theory and to related exploration technology.

One of those interviewed, an honored and notable geoscientist and ore finder, said: "Those people (advisors on minerals) in Washington are economically naive."

We must agree.

Conclusions

The American mineral exploration industry, viewed as a whole, is in an advanced state of disarray. Discovery records are very poor; morale is low; and not a few corporate groups have recently reduced effort substantially, or completely ceased exploration. To a certain extent, this exploration malaise extends worldwide. However, the domestic industry, because of its generally high cost nature and other factors, has been affected more than others.

Many explorers, looking backward, think that the domestic mining industry passed, unknowingly, some subtle point of no-return, ten or more years ago. This fundamental change appears to be the result of the following main factors: 1) increased recycling, materials substitution, and general economising in the use of many metals; 2) near saturation of markets in the main industrialized countries; 3) increased concentration of primary metal production in state-owned enterprises, and 4) the resulting reduction of private industry's share of world markets. [For a more detailed discussion, see: Fujisaki, A.; CIMM Bulletin, October, 1983.]

At present, most metal markets are cyclically depressed. However, there is an increasingly strong belief and evidence that these markets are also structurally unsound, and that profound changes are inevitable.

In effect, the basic factors point to a long period of over-supply for many metals, not scarcity. This belief is increasingly apparent in boardroom decisions. Exploration managers are attempting to switch manpower and money from base metals, to the currently attractive precious metals field, and in some cases, succeeding. This temporary haven will not provide satisfactory shelter for all those now interested in precious metals, and more exploration groups will be eliminated.

The strategic materials business in North America is not large or profitable enough to attract major, long-term explorers. There is some strategic materials exploration in countries with centrally planned economies, such as China and the U.S.S.R. Their purpose appears twofold: fulfill domestic requirements, and to supply export materials to earn "hard currency". In North America, the basic problem in strategic materials exploration is that the perceived economic gains do not appear commensurate to the risk involved. Especially bothersome is the fact that foreign countries can produce vast quantities of high-grade materials at costs well below that of any possible domestic producer.

Mineral exploration is a big chip gambling business. Unlike roulette, blackjack or craps, the chances of success cannot be calculated before the play begins. Furthermore, the actual rules of the game are only dimly perceived, and outside forces keep juggling the political, economic and social environments of the game site.

The "law of gambler's ruin" (Slichter, L.B., Jackling Lecture, Mining Engineering, May, 1960) is an elemental rule of gambling probability. The law is expressed mathematically by: $Pr=e-NPs$, where N=number of ventures; Ps=probability of success for a single venture; and Pr=chance that N ventures will fail in a row.

It can be shown that if ten ventures are attempted, each with a 10 percent chance of success, there is a 36 percent chance that all ten ventures will fail in a row.

There are no accurate, published mineral industry figures on exploration success rates, or how much ore has been found for the money expended, unlike the oil & gas industry. According to generally accepted figures, the new field, wildcat discovery success ratio in the petroleum industry for the last few years is approximately 1:9. Depending on the type of basin and available geologic information, the ratio ranges from 1:3 to 1:20. (Mear, C.E., V.P., Southland Royalty, personal communications, November, 1983). The Superior Oil Company, a highly successful independent oil company, has maintained a 1:2 success ratio for the past 5 years.

Published mineral industry figures are, in general, inaccurate or misleading because they have depended to a great extent on voluntary selective data disclosure from examples representing only a small percentage of the total exploration money expended. It is concluded, perhaps cynically, that the industry's lack of co-operation is deliberate, in order to divert attention from the true facts. It appears that luck may still play a significant role in the results of modern mineral exploration.

A few rough success estimates have been compiled. These, coupled with "off-the-record" figures provided by practicing experts, seem to settle around the 100 to 1 level. That is, for the minerals industry as a whole, for every 100 raw prospects of any type, tested in any fashion, only one will prove to be an ore body, of any size. Substantial ore bodies, i.e. one large enough to return the explorer's total exploration expenditures, and a profit, are even scarcer. This may equate to 1 in 1000, or 1 in 1500. Of course, most individual explorers are certain that his group can beat these odds. This is rarely the case, and even then, "luck" must be considered. [One is reminded of the joke: "Why do you insist on playing here? You know it's a crooked game."

"Yes, but it's the only game in town!" (Attributed to Canada Bill Jones, a riverboat gambler, ca. 1880)]

If the 1 percent success estimate is reasonably correct, and is placed in the formula, for say, 50 ventures, then there is a 60 percent chance that all 50 ventures will fail consecutively. In this same case, a 100 percent improvement in the odds, to 1 in 50, or 2 percent, reduces the chance of total failure to 36 percent, only a 40 percent fall from 60 percent.

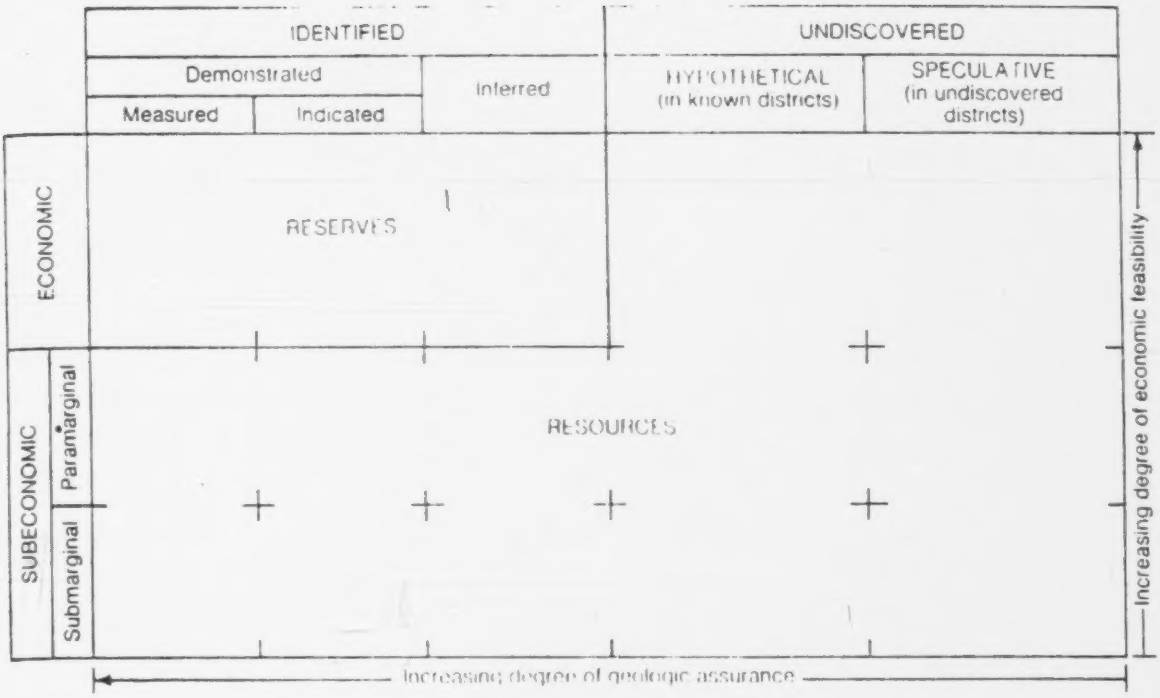
This elementary law of probability is not normally employed, or perhaps truly understood by mineral explorationists. Geopsychology should, perhaps, be a required course of study.

Resources vs. Reserves

For the purpose of this report we will employ the USGS-USBM terminology for classification of mineral resources. See chart on page 4a; definitions on page 4b . This classification is familar to most mineral people. However, it should be clearly understood that geologists and engineers can, and do, substantially disagree over the exact classification of any particular "identified" deposit.

The chart's undercaption, "increasing degree of geologic assurance" has, we think, led non-geologists (and some geologists) astray in two ways: 1) the left hand margin is confused with certainty, and 2) it can be, and is, often equated to the level of assurance that geoscientists can place on why ore bodies are located in one particular place and not another. This is definitely not the case.

According to Bailly, P.A., "The Problems of Converting Resources to Reserves, Mining Engineering, January, 1976, pp. 27-37; "...most


IDENTIFIED
UNDISCOVERED
Demonstrated
Measured
Indicated
Inferred
HYPOTHETICAL (in known districts)
SPECULATIVE (in undiscovered districts)
ECONOMIC
SUBECONOMIC
Paramarginal
Submarginal
RESERVES
RESOURCES
Increasing degree of economic feasibility
Increasing degree of geologic assurance

Mineral Resources Classification System

Definitions

- **Identified Resources:** Specific bodies of mineral-bearing material, the location, quality, and quantity of which are known from geologic evidence and, if they are in the demonstrated category, are supported by engineering measurements.

  —*Reserve:* That portion of the identified resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination. The term ore is used for reserves of some minerals.

  —*Identified Subeconomic:* Identified resources that may become reserves as a result of changes in economic, technologic, and legal conditions.

- **Undiscovered Resources:** Bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory. Exploration that confirms their existence and reveals quantity and quality will permit their reclassification as reserves or as identified subeconomic resources.

  —*Hypothetical Resources:* Undiscovered resources that may reasonably be expected to exist in a known mining district under known geologic conditions.

  —*Speculative Resources:* Undiscovered resources that may exist either as familiar types of deposits in a favorable geologic setting where no discoveries have been made or as unfamiliar types of deposits that remain to be recognized.

Measured, indicated, and inferred resources include both reserves and identified subeconomic resources. They are defined as follows:

- **Measured:** Identified resources for which tonnage is computed from dimensions revealed in outcrops, trenches, workings, and drill holes and for which grade is computed from the results of detailed sampling. The sites for inspection, sampling, and measurement are spaced so closely and the geologic character is so well defined that size, shape, and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits, which are stated, and no such limit is judged to be different from the computed tonnage or grade by more than 20 percent.

- **Indicated:** Identified resources for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projection for a reasonable distance on the basis of geologic evidence. The sites available for inspection, measurement, and sampling are too widely or otherwise inappropriately spaced to permit the mineral bodies to be outlined completely or the grade to be established throughout.

- **Inferred:** Identified resources for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit and for which there are few, if any, samples or measurements. Continuity or repetition is assumed on the basis of geologic evidence, which may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred reserves or resources should include a statement of the specific limits within which the inferred material may lie.

'proven' mineral reserves of metals are known, at best, within a plus minus 20% margin of error, and that increasingly larger margins of error must be assigned in this order to inferred, hypothetical, and speculative mineral resources." We agree. "Appraisals" of, and reliance on, undiscovered mineral resources is, at best, a highly uncertain exercise.

Mineral pundits, natural resource theoreticians, popular writers, and the press, often do not carefully and accurately define their resource frame of reference. The resulting semantic confusion is one of the the principal reasons "futurologists" produce such greatly differing estimates of the raw materials available to mankind now, and in the future.

The U.S. does contain very large quantities of identified, subeconomic resources of most common metals. For example, these include the very large, low-grade copper-molybdenum zones surrounding most southwestern porphyry copper deposits; the copper-nickel-cobalt mineralization in the Duluth Gabbro; copper, zinc, nickel and cobalt in the massive pyrrhotite deposits of Maine and Virginia; and the low-grade taconite iron ores of Michigan and Minnesota. Many other examples could be presented.

There are also large, subeconomic resources of some strategic materials not mentioned above. These include the large, identified deposits of manganese-bearing rocks at Artillery Peak, Arizona; Aroostook, Maine; Cuyuna Iron Range, Minnesota; and the Pierre Shale of North Dakota.

The lateritic rocks of California and Oregon contain substantial quantities of chromium, cobalt and nickel. Chromite occurs as a very common accessory mineral in some basic rocks, such as peridotite, throughout the world. American peridotites are not exceptions.

Genetic theory, geology, exploration technology and methodology are not the real problems. There are enormously large, identified, currently subeconomic resources of both base and strategic metals present in the United States.

The main items required to change these resources into reserves of "ore" are human resources, land, and expectations of economic reward. An economic reward requires a favorable blend of national and international monetary, social and political factors, which are very difficult to foresee.

Human resources covers the best scientific, technical and organizational capabilites of Americans. This resource is assured if the other requirements are met.

Land is the all important, but commonly overlooked requirement for mineral exploration and resource conversion. Land, no matter how geologically favorable, is worthless to the explorer unless both the surface and the subsurface is available for exploration AND exploitation. Firm, definite and long-term surface and mineral tenure is an absolute requirement for expectation of economic reward.

The United States' land inventory is fixed. The withdrawal of very large areas of Public lands from mineral exploration, for "higher and better" uses, has had, and will have, an increasingly serious and deleterious effect on our whole domestic mineral posture. At base, this appears to be a political problem which will not be easily remedied.

The effects of this governmental policy have been compounded by "creeping urbanization". Cities and their satellite suburbs sprawl across the countryside. "Second homes", vacation sites and other similar land uses have become increasingly common and popular.

This type of land use creates, for practical effect, private land withdrawls, for many explorers cannot afford the time and acquisition costs in such areas, and in any event, their exploration activities are not welcome.

Most everyone will agree that we need mines, waste disposal sites, weapons testing facilities, prisons, etc., but definitely not "in our backyards."

If large blocks of readily available land are not available for mineral exploration, it is dangerous and of modest practical use to strongly rely upon the benefits allegedly to be derived from development of satellite technology or computerized "mineral endowment" predictive metallogeny, or direct subsidies, or whatever.

One of the very few geologic certainties is that we do not know where the next ore body (of any type) will be found. Most ore bodies occupy very small areas, at the state or continental level. However, the zone of "favorability" in which they may occur is much larger.

The "Colorado Mineral Belt" (Tweto, O., Ore Deposits of the United States, Vol. 1, pt. V, p. 551; AIME Graton-Sales Volume, 1968) is a well known, intensively mineralized zone crossing western Colorado. The known mines in this belt have produced very large quantities of silver, gold, molybdenum, copper, lead, zinc and other metals. This roughly rectangular area of about 8,000 square miles, extends southwesterly from Boulder to a point about 75 miles from the southwestern corner of the state.

It is quite possible that those employing satellite technology and "predictive metallogeny", coupled with new genetic theory, could postulate the presence of several unidentified, major mineral deposits in this belt.

The belt also contains not a few important and popular recreation areas and their associated "infrastructure". These include skiing meccas such as: Loveland Basin, Breckenridge, Aspen, Ashcroft, Vail, Crested Butte, Cramer Hill, Telluride, etc., There are scores of recreational lake areas; many hiking trails, wildlife preserves, historic monuments, etc., etc., ad infinitum.

In short, no matter what technology says, or "predictors" believe, the hard fact remains: large portions of the area of this important mineral belt are not practicably available for exploration.

Many other similar examples could be given.

The seriousness of the land availability problem cannot be overemphasized. According to the Census Bureau, the median estimate of the American population in 2010, is 275.0 million. The land availability situation is an important and difficult exploration problem now; the pressure of the additional population will compound this headache.

The domestic minerals industry is expected to produce more and more minerals from less and less land - a task extremely difficult, or impossible to achieve. Further, domestic deposits are expected to compete with mines operating on low cost, high grade ores in foreign countries.

Many mineral producing countries of the world have partially mitigated the land problem by placing all mineral rights in the hands of the state. In some, the rights were derived from the power of the Crown;

in others, by government dictat. These mineral rights can be leased, or otherwise held, by individuals, corporations, etc. Since the state owns the minerals, it can, at least in theory, apply the principle of "the greatest good, for the greatest number", in a fashion exactly similar to our domestic application of "eminent domain" to water reservoir sites, highways, etc.

It may be the opportune time for American mineral policy makers to consider nationalization of mineral rights. The hidebound traditionalists of the domestic mineral industry will violently recoil at the thought. Nevertheless, the idea has been previously proposed in a carefully reasoned paper dealing with future domestic mineral resources (Ridge, J.D., USGS Professional Paper 921, pp.12-16)

Many non-metallic minerals, e.g. oil and gas, oil shale, phosphate, coal, potash, trona, etc., which occur on government owned lands, are in effect, nationalized. The rights to minerals, metallic or non-metallic, on government owned, reacquired lands, must be leased from the government.

At the thought of nationalization, mining trade groups, representatives of mining companies, and most explorationists will undoubtedly invoke the names of the small miner and prospector (a largely ficticious character), free enterprise and the sacredness of the present claim system.

It may be the correct moment to study the merits of an all minerals leasing system; one which will ensure exploration activity and reward the diligent. Exploration could, at least theoretically, then be directed to the very best areas, not to the best areas where land is readily available.

Genetic Theory

Most currently employed theories of ore genesis are basically derived from developments in the understanding of plate tectonics and continental drift.

The latter process is the fundamental concept in geoscience today. Unquestionably, it has led the greatest mental revolution in geoscience since its inception.

Until the mid 1950's, most geologists accepted that the continents had always had approximately the same shape and location as they have today. A few people, most notably the German, A. Wegener in 1912, suggested that about 200 million years ago the continents were packed together in one universal land mass called "Pangaea". Wegener called attention to the "jig-saw" piece matching effect of the South American and African continents; certain similarities in geology, plant and animal life; and in paleoclimates of various continents.

This basic concept received little support from other geoscientists and the idea was essentially forgotten. However, in the mid 1950's, the concept received a strong boost from data collected from "the well known" deep sea drilling program. (Derry, D.R., 1980: A Concise World Atlas of Geology and Mineral Deposits)

Very briefly, the deep sea drilling program determined that the major ocean basins of the world contained substantial "mountain ranges" caused by igneous rock flow from major crustal rifts; that the remnant magnetism preserved in the rock had the same "signature" on each side of the rift zone; and, that a particular flow's age was proportionate to its distance from the rift. In the Atlantic, for example, it was shown that the two sides have progressively parted over a period of 180 million years. Similar rifts have been found in all oceans.

This "sea floor spreading" indicates that the continents form integral parts of the lithosphere's plates, and move with them something like rock carried in a glacier.

Since the earth's diameter appears to be fairly static, the "old crust" is thought to be "subducted", that is, assimilated at points where moving crustal plates meet the static plates.

Structural, volcanic and many other complex geologic phenomena occur at both ancient and current plate contacts and subduction zones. Some of these phenomena are related to the origin and development of various types of mineral deposits.

Very simply, this plate tectonic theory caused a revolution in man's understanding of the nature and genesis of ore deposits. It can be demonstrated that certain types of mineral deposits are found to be associated with plate tectonic effects in a specific fashion.

The growth of this knowledge and theory is the e=mc2 equivalent of geologic science. In the same light, however, there is still very much more to learn concerning the finer details of the total process.

This concept, or tool, is definitely useful in predicting which areas may be most favorable for the location of certain types of mineral deposits. However, it is not yet successful, and most probably may never be, in pin pointing the exact location and quality of these mineral deposits.

The most definite and important association of mineral deposits to subduction zones is that of porphyry copper deposits. The Rocky and

Andean mountain ranges of North and South America lie near, or at, subduction zones. The porphyry copper deposits found in these ranges contain much of the world's identified copper resources. A similar subduction zone in the southwestern Pacific also contains porphyry copper deposits (Derry, D.R., 1980).

All subduction zones are not known to contain porphyry copper deposits, however. A subduction zone occurring along the Aleutian Island arc apparently does not contain true copper porphyries, although other types of mineralization have been identified.

There have been recent attempts to produce an overall plate tectonic classification for all types of ore deposits (Guilbert, J.M., 1981, in: Relations of Tectonics to Ore Deposits in the Southern Cordillera; Arizona Geological Society Digest, Volume XIV). [see Appendix A]. This, and similar classifications are quite controversial and no one format is widely accepted by explorationists. Most of the doubters do not trust the "simplification of nature" required and believe that another generation or two will be required to fully understand the ore genesis problem.

In effect, for the earth's crust, we are considering a massive physio-chemical system of almost infinite complexity, the fabric of which has been further complicated by geologic processes occurring and and reoccurring over a period of about 4 billion years. We should not waste our time seeking, or expecting to find, as in physics, basic universal laws which apply to all things. Too often "we try to simplify nature in order to understand it." "Mother Nature is a bitch".

Modelling

Modelling by analogy has always been with us, even in flint mining days.

Analogue modelling is simply, deductive reasoning. If nickel deposits are known, from observation and/or report, to occur in a dark basic igneous rock of certain type, then that is the preferred place to start to look for other nickel deposits.

"Eye ball assay" prospectors, using such simple analogy, identified practically all of America's outcropping mineral resources.

The gradual accretion of general scientific, as well as geologic knowledge, has enabled us to construct semi-detailed and reasonably accurate analogue models for many types of economic mineral deposits.

Most models now employed are built on a subjective base; objectivity is difficult to input, and is badly needed.

Currently, modelling by analogy is more important, and has proven to be more useful than genetic theory in mineral exploration. They should both be employed together as much as possible. However, if these two conflict, then modelling by analogy is followed, for the idea is much easier to sell to non-technical management, and has proven to be more reliable than our tentative genetic theories. It can be fairly stated that no ore body has been found by genetic theory alone.

In general, oil companies use conceptual models for petroleum exploration, since most of their analogue model targets have long been tested. Conceptual modelling "is the natural progress of maturation in exploration." (Dahlstrom, C., VP, Chevron Resources, personal communication, 1983) The mineral industry has not reached this stage in its development, because the geologic variables cannot be quantified as yet.

In fact, we are not certain of just which variables are significant.

Total integration of all related geologic, geochemical and geophysical data is required for precise modelling. This ideal is far from realization, and may never be obtained. Increasing specialization in various exploration related fields has created "communication problems"; more generalists are needed.

Stanford Research Institute has developed a computer program consisting of numerous ore deposit models. The "Prospector" as the system is called, uses all available geologic data, and mathematical models have been developed by recognized experts in a particular type of deposit. Ideally, such a system may be able to predict whether a certain area could contain an ore deposit, provided the input geologic data base was as accurate as that of the particular model to which it is compared. This approach needs many more years of work, and a much larger and more accurate data base before it can be used as an effective exploration tool.

Predictive Metallogeny

In the last 15 to 20 years, a considerable amount of theoretical attention has been given to the employment of statistical and probabilistic mathematical techniques for predictive metallogeny in resource assessment.

The ability to predict the location, size and quality of undiscovered mineral resources is the ultimate hope of geologists.

At the present time, this goal is far, far beyond our grasp. Some predictive theoreticians, however, ignoring this hard fact, have presented papers and made statements which may have seriously deluded politicians, governments, long-term economic planners and other non-geologists. Witness the Club of Rome's misinterpretation of mineral related data.

There are definite and strong differences of opinion concerning the practical utility of this technique on-going between the risk-taking explorationists and the theoreticians who are preaching the latest version of "geo-truth".

So far as can be determined, few, if any, profit oriented explorers employ these methods in any substantial fashion. Many regard these techniques as nothing more than mildly interesting "computer tinkering", since they have always employed a "start with the known" approach to exploration.

Predictive metallogeny has two main items of theoretical application: 1) regional, or continental resource appraisals, and the preservation of potential mineral land; 2) exploration planning and prospect identification.

The first use has been heavily employed by government geologic surveys (American, Canadian, Russian). The U.S.G.S. relies on these techniques to appraise the mineral potential of federal lands proposed to be withdrawn for various purposes. Most explorationists feel that this use is of very limited practical utility, particularly since the actuality of the appraisal will never be tested by drilling.

Papers, given at a 1982 symposium on the subject have recently been published (Geoscience Canada, Vol.10, No.2, June, 1983: Appendix B). The papers accurately depict the current "state of the art", and the battle between the theoreticians and the pragmatists. They should be carefully reviewed. Selective quotations from one of these papers effectively summarizes our, and a great majority of those interviewed, opinions.

G.W. Manard, Kidd Creek Mines:

"It is instructive to compare the foregoing characteristics of the two successful company exploration programs with the characteristics of many of the exercises in predictive metallogeny carried out by government or academic organizations in recent years.

1. Motivation. Most predictive metallogeny exercises, or resource appraisals, are carried out at the instigation of political or economic planners, who have little understanding of the capabilities or the limitations of economic geology.

2. Staff. The individuals who do the work, although they may be skilled scientists, commonly have little background in the applied aspects of geology.

3. Data base. Many evaluations are based on published geological maps which have been made by geologists who are relatively uninterested in mineral deposits and who are not trained to recognize the peripheral indications of hidden mineral deposits. In most Canadian provinces, the compilers of metallogenic maps commonly pay little attention to the assessment files with their wealth of data of economic mineral occurrences.

4. Misuse of data. Many attempts are made to produce quantitative data, usually on the basis of questionable statistical assumptions, or the equally dubious concensus of a group of "experts" on the region involved or the deposit type sought.

The "quantitative" data from such studies, taken out of context and used by economic planners or "simplified" by the media, can by very misleading. Bad economic planning and misuse of public funds can result from the improper use of so-called quantitative resource appraisals."

From his Conclusions:

"Controversy has surrounded many of the applications of the technique, usually being sparked by violent differences of opinion between private industry and the agencies responsible for the studies."

"The fundamental conflict between the academic approach to predictive metallogeny and that of the exploration geologist is displayed dramatically in a brief but spirited exchange of Letters to the Editor generated by DeVerle P. Harris' paper entitled 'A subjective probability appraisal of metal endowment of Northern Sonora, Mexico' (1973). To attempt here a summary of the paper and the discussion it provoked is not feasible. Suffice it to say that the author's work 'yielded an expectation of approximately 2600 tons of metal per square mile' in this study area, and led him to estimate that roughly one-quarter of this could be found and mined profitably under the economic conditions of the time. The paper was written in 1973; in hindsight, one wonders what part of the expected metal would have been mineable three years later, in 1976, under the drastically different economic conditions that prevailed then. Not surprisingly, Sobel, an experienced economic geologist with a fair amount of field time in Sonora, vigorously and not too

> politely disputed both Harris' methods and his findings. He offered his own conclusions as to how the study could be summed up: 'Ten experienced geologists feel that a good chance exists to find new mineral deposits in Sonora; the choice sites to explore are close to known deposits.' The correspondence ends with the author's reply to the criticism, in which he defends his position with the interesting statement 'it matters not that the task is a dirty one, that the phenomenon of mineral occurrences is not completely understood, or that information is often too meagre to give high or even moderate reliability to estimates. Mineral resources appraisals often must be made in spite of these obstacles.' Accepting that there is a general and increasing need for mineral resource appraisals is not difficult; accepting that they must be quantitative is more difficult, in view of the very problems expressed by Harris. The weaknesses in the basic data and assumptions used can be expressed properly when the communication is in the form of a scientific paper exchanged between consenting adult earth scientists. The problem arises when the quantitative conclusions are taken out of context by members of the communications media, politicians or bureaucrats, and unknowingly used in an improper manner. Such misuse, as noted earlier, can lead to unwise expenditure of public or private funds, unfair taxation and unrealistic mining laws."

The base problem may be summed up as: the theoreticians are trying to identify and quantify RESOURCES; the pragmatic explorers are trying to identify and quantify ORE. Economics cannot be divorced from mineral exploration.

Technology and Methodology

Technology and methodology are the basic tools of exploration. Without them, there is no chance of filling society's mineral needs.

Technology and methodology are commodity dependent. Much of current practice was developed for uranium, porphyry copper and multi-metal massive sulfide exploration. Since there has been very little domestic exploration for strategic materials within the last 3 decades, no significant specialized technology and methodology has been developed for these materials.

Specialized techniques are not required for cobalt or PGM associated with copper, nickel and iron sulfide minerals which normally have detectable electromagnetic signatures. Chromite and manganese oxides can be detected using certain electromagnetic and other geophysical techniques. Because of the association between many strategic metals and mafic/ultramafic (basic) rocks, current technology can and may locate resources of this type. However, no geophysical techniques are available which can identify economic concentrations of metals present in th earth's crust as carbonates and/or silicates e.g. manganese carbonate deposits and nickel-cobalt silicate minerals in laterites. Some success has been achieved in distinguishing carbonate and silicate minerals in surface outcroppings using satellite imagery, but even a thin veneer of post-mineral cover nulifys the usefullness of this technique.

It then falls to geochemistry and geology to be the primary tools employed in the search for these types of deposits. Indeed, a totally integrated data base utilizing all available technology and methodology, plus the incentive to search, is needed for any successful exploration program.

In general, data collection techniques are much more advanced than data interpretation. The explorationist stands neck deep in vast seas of data, which cannot be really accurately, and usefully, interpreted. Computers are very useful in manipulating this data in various fashions, but interpretation still lies in the minds of men. Preconceived ideas are often interjected into interpretation, to the detriment of exploration success.

Geochemistry, if it can be employed, is usually a much more useful exploration tool than geophysics, since it generally directly measures the element(s) sought, not its electromagnetic analogue.

Faster, more accurate, and broad spectrum chemical, or other analytical methods are badly needed, particularly those which deliver results in real time.

Most geophysical techniques are approaching the absolute limitations imposed by physical laws. In any event, we are only searching 150 or so meters into the earth. There is also too much man-made "background noise" in received signals. Current geophysical equipment cannot adequately screen out these "noises". Nor can it certainly distinguish between various sulfide minerals and graphite.

Lower cost and faster drilling techniques are greatly desirable. Since the ultimate test of any theory, model concept or technology is made with the drill rig, this technique should be much more advanced than it is.

Cheaper drilling would allow us to place improved borehole geophysical instruments further into the earth, greatly increasing the volume of rock swept by the signals. Coupled with accurate, real time, rock analytical techniques, we could then be reasonably certain nothing of significance was overlooked in the areas tested.

Institutional Factors

Some major barriers to effective mineral exploration are: governmental mineral policies, which vary from area to area, from commodity to commodity, and from time to time; environmental rules and regulations; and, population growth which creates largely unplanned urbanization.

Land withdrawals, without knowing what mineral potential is being withdrawn; zoning of mineral lands for recreation and housing, both without considering the nation's long-term mineral needs, are two of many specific points.

Neither corporations, nor the essentially ficticious "small prospector" will explore for minerals without expectation of future economic benefits. As the long-term view of these potential benefits becomes increasingly obscured by hazy and variable government policies, tax law, etc., interest in mineral exploration declines.

A strong, definite, national minerals policy, designed for the long-term, is a vital need. There has been much lip service given to this subject over the years, but in actuality, nothing much has changed in the last 3 decades.

Corporate Barriers

The American mining industry has created many of its own barriers.

For example, geologic information and other mineral related data are critical items in the mineral exploration process. They are pieces of the ore deposit puzzle, and any fragment may be a key piece.

Older geologic data must be constantly reviewed in the light of new knowledge, concepts, or economic conditions.

No old mining district is positively dead in a geologic sense. The next minor geologic-mineralogic discovery may bring it to life.

Because of this fact, regional or national collective data pools, core storage facilities, etc., are desirable. The Bureau of Mines, and a few State agencies have established, in a very limited fashion, core libraries and data pools in some areas. However, the information obtained is given at the discretion of the individual explorers, and "proprietary" (self-defined) data is withheld. Indeed, scores of thousands of feet of drill core are thrown away every year. Large amounts of time and money are wasted in replicating previous exploration work. It is quite common, in old mining camps, to find properties which have been drilled two or more times. Yet no one knows what was found by the drilling, or what happened to the core samples.

The industry, as a whole, will never voluntarily agree to public domain data pooling. Here we mean actual physical data and samples, not collective statistics on industry wide drilling, geophysics, etc. Some government action is required. Explorers for oil and gas are required, by law and regulation, to supply copies of all data gathered from their activities on public and private lands. The overriding public welfare principle is accepted. Those who explore for minerals should be required to do the same, and to accept the principle.

In the Canadian provinces, law and regulation requires the filing of accurate semi-public information on the type, location and cost of exploration work. If this work is not actually performed, an official can deny, or cancel rights to the claims. Such is not the case in the United States, where in most cases, the limited information required is carefully drafted by the explorer to yield little, or nothing of interest. Further, many "small miners'" exploration work consists solely of going to the recording office and swearing that they did the required work.

The domestic mineral industry has had an unacknowledged subsidy for many years, i.e. the possessory right to public lands through mining claims, which can be held indefinitely for $5.00/acre/year. We personally know of claims which have been held by a major mining company for over 20 years, without any serious attempt to test, or develop their mineral potential. Such "non-activity" is common.

These are, undoubtedly, among the cheapest mineral rights in the world. The taxpayers' gift should be reciprocated by return of all the data obtained from the land.

The short sighted and selfish attitudes held by the industry have damaged the nation's mineral posture.

There is an undercurrent of corporate belief, increasing in recent years, that mineral exploration may not be worth the considerable risk and effort involved. During the Mining Congress Convention, in September, 1983, D.R. Cook, a Vice President of Freeport Minerals presented a paper containing statistics that indicated that a world-class ore deposit cost approximately $290 million to acquire, either by exploration or purchase. This is based on worldwide 1982 exploration expenditures of $665 million by 24 major mining and energy companies, and on the discovery of 69 world class deposits in the past 30 years, or an average of 2.3 deposits per year. World class deposits were defined as those that consistently returned a profit despite recessionary periods of low metal prices; that the deposits were of a magnitude to significantly affect a medium-sized corporation's profit; and that they should be in the lower one-third of cost per unit of metal sold for all producers.

[Note: Cook lists 22 deposits world class deposits discovered in the United States during the last 30 years. Others could be included: the molybdenum deposit at Questa, New Mexico; and the polymetallic deposit at Bald Mountain, Maine. However, of these 24 deposits, less than half are now operating, and possibly returning a profit.]

There is a strong aura of malaise, of general pessimism, hanging over the mineral exploration industry today.

There has always been a self-taught, optimistic and fundamental view that the American metal mining industry, even though unbeloved and unappreciated, was of critical importance to the nation, its economy and its political power.

It would never be publically admitted, but the fact that neither Japan nor West Germany has a very large metal mining base, despite their substantial economies, is beginning to be thoughtfully considered.

The malaise is also affected by a growing shortage of favorable public lands, costly exploration, poor discovery rates, low grade ores, generally low return on capital, etc. For example, why make an expensive and risky search for copper in America, when Chile has a large inventory of identified, but unexploited deposits?

Strategic Materials

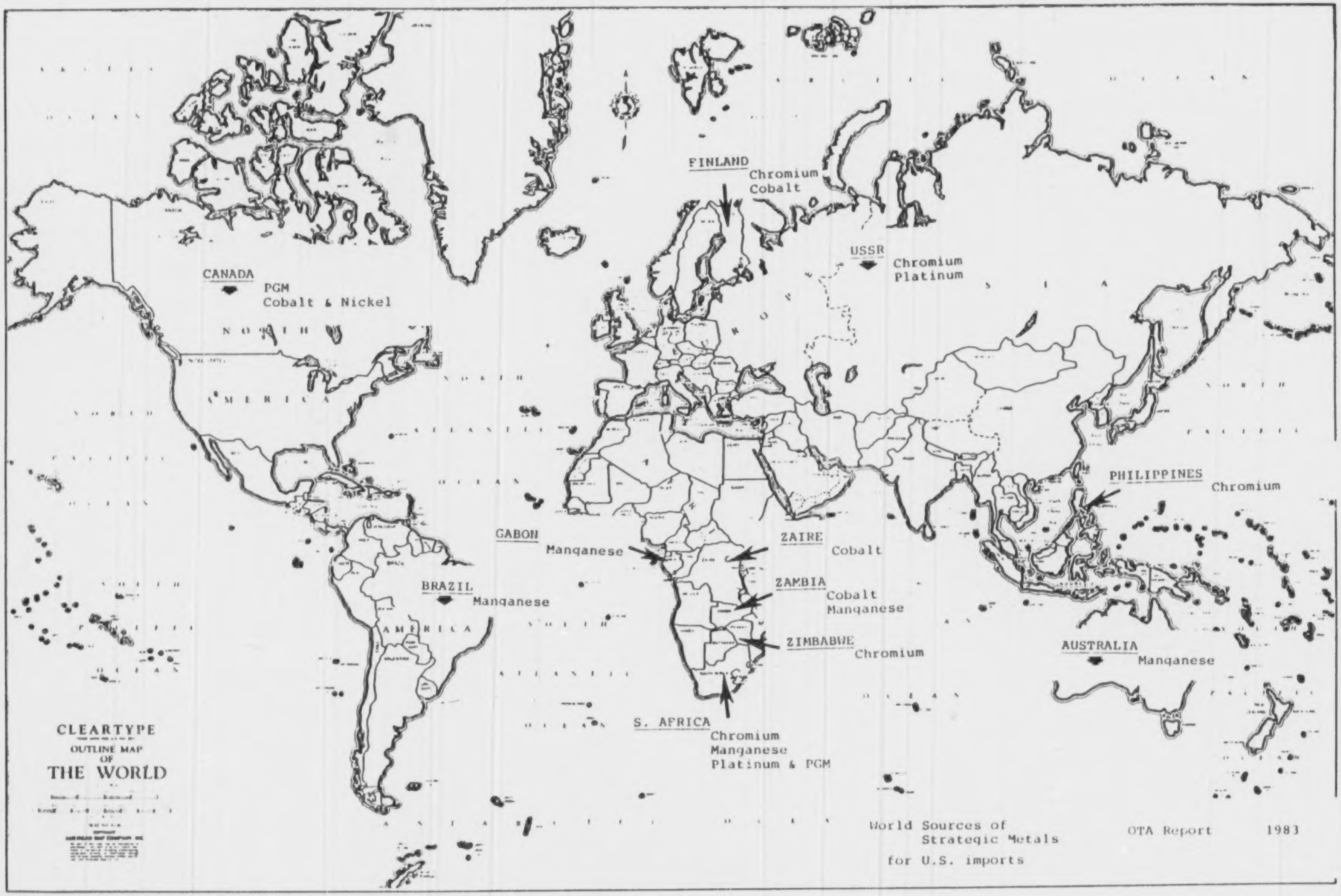
With no expectation of future economic benefits, few, if any, companies are exploring for strategic materials in America; platinum group metals may be a minor exception. Additional resources may be discovered. However, they will probably not be able to compete economically with foreign sources without some type of long-term, guaranteed incentive arrangement.

As governments change, so do policies on national mineral priorities, imports, stockpiles, etc.

Most corporate explorers maintain 5-year, or longer, corporate plans, which are adjusted annually by inputing information on current economics, finance, and appraisals of future market economy needs.

The wide, year-to-year variations in the whole strategic material field are unsettling. "It's too risky a game." Two other items are of considerable concern: a) The large quantities of high-grade reserves and resources controlled by foreign competitors, who could easily reduce world prices; and b) The fact that much of the unit value in some of the strategic materials is derived from "value added" processing, as in ferro-chrome, chromium metal, ferro-manganese, etc. To some extent, this makes the small to medium sized producer dependent upon the ore buyer.

Current growth activity in the material science field, e.g. graphite-metal composites, glass fibers, ceramics, etc., is also causing some worry. "The cobalt market could be replaced by a clay pit."



CLEARTYPE
OUTLINE MAP OF
THE WORLD
CANADA
PGM
Cobalt & Nickel
FINLAND
Chromium
Cobalt
USSR
Chromium
Platinum
PHILIPPINES
Chromium
GABON
Manganese
ZAIRE
Cobalt
ZAMBIA
Cobalt
Manganese
ZIMBABWE
Chromium
BRAZIL
Manganese
AUSTRALIA
Manganese
S. AFRICA
Chromium
Manganese
Platinum & PGM
NORTH AMERICA
SOUTH AMERICA
NORTH ATLANTIC OCEAN
SOUTH ATLANTIC OCEAN
NORTH PACIFIC OCEAN
SOUTH PACIFIC OCEAN
ARCTIC OCEAN
EUROPE
ASIA

World Sources of
Strategic Metals
for U.S. imports

OTA Report 1983

OTA Report   The Strategic Metals   Summary Sheet

	Chromium	Cobalt	Manganese	Platinum Group Metals
Uses	manufacture of stainless steel	high-temperature alloys, permanent magnets, and high speed cutting tools	steelmaking	catalysts in the control of auto emissions, petroleum refining, and electrical/electronic components
Net Import Reliance	88%	91%	99%	85%
Sources	as chromite: South Africa (44%) U.S.S.R. (18%) Philippines (17%) Other (22%) as ferrochromium: South Africa (71%) Yugoslavia (11%) Zimbabwe (6%) Brazil (3%) Other (9%)	Zaire (38%) Zambia (13%) Belgium-Lux'g (11%) Finland (6%) Other (32%)	as manganese ore: Gabon (32%) S. Africa (24%) Australia (18%) Brazil (15%) Other (11%) as ferromanganese: S. Africa (42%) France (25%) Other (33%)	S.Africa (56%) U.S.S.R. (16%) United Kingdom (11%) Other (17%)
Stable Sources	Finland Philippines	Australia Canada Finland	Australia Brazil France	Canada
Prices	chromium metal: $3.75-$4.25 per pound high-chromium ore: $110 per tonne Turkey high-iron ore: $52 per tonne S.Africa	producer price for cathodes: $12.50 - $17.26 per pound	metallurgical ore, 46-48% Mn, per LTU contained Mn, c.i.f. US ports $1.58 - $1.68	$475 per ounce
Amount Recycled	in 1982, 12% of chromium demand	in 1982, about 420 tons: 8% of est.consumption	insignificant	about 320,000 oz nontoil; 1 million oz toil basis
Resources	Most of the known subeconomic resources in the United States are in the Stillwater Complex, Montana.	Major subeconomic resources in the Duluth Gabbro Complex, northern Minnesota.	Identified, subeconomic resources include: Artillery Peak, Arizona Cuyuna Range, Minnesota Aroostook, Maine	Most of the known, probably economic resources are in the Stillwater Complex in Montana

Source: US Bureau of Mines Mineral Commodity Summaries, 1983

Introduction

Chromium, cobalt, manganese and the platinum group metals have been selected for this study as those materials for which the United States would be most vulnerable to interruptions in supply. See OTA definition in Foreword of this report.

Selected, basic information on these four materials is summarized in the table on page 1a .

The major producers of these strategic materials are South Africa, Zaire, Gabon and the U.S.S.R.

No group is actively exploring for these materials in the United States. Several companies, however, are trying to convert identified, subeconomic resources of cobalt and the platinum group metals into exploitable economic reserves. World markets, politics and socio-economic conditions make this difficult. Even if these programs are successful, it is probable that the amounts of material produced will not be at all significant in the context of America's current and long-term requirements.

Chromium

General

No satisfactory substitute has been found for chromium in the production of stainless steel.

The only economic mineral of chromium is chromite. Compositionally, three general kinds of chromite are recognized: high-chromium, high-iron and high-aluminum. Types are characterized by percent Cr2O3 and the Cr:Fe ratio.

Origin

Chromite is mined solely from massive to heavily disseminated

World Chromite Reserve Base

(Data in 000's short tons, gross weight)

Location	Reserve Base
South Africa	2,500,000
Zimbabwe	1,100,000
Finland	28,000
Turkey	5,500
Philippines	3,300
Centrally Planned Economies	22,500
Other Market Economy Countries	14,300
United States	-

Source: USBM Mineral Commodity Summaries, 1983, page 33

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Economic Chromium Mineral

Chromite $(Mg,Fe^{++})(Cr,Al,Fe^{+++})_2O_4$

high-chromium: containing 46% or more Cr_2O_3
and has a Cr:Fe ratio of 2:1 or more

high-iron: containing 40-46% Cr_2O_3
and has Cr:Fe ratio of less than 2:1

high-aluminum: containing more than 20% Al_2O_3
and more than 60% combined Cr_2O_3 and Al_2O_3

Source: USGS Professional Paper 820, page 112 segregations in ultramafic or mafic igneous rocks.

Chromite ores are usually assigned to one of two classes on the basis of deposit geometry, as well as the petrologic character and tectonic setting of their host rocks.

Stratiform deposits are sheet-like accumulations of chromite that occur in layered ultramafic to mafic igneous intrusions. The intrusions are typically of Precambrian age and occur in intracratonic terrains. A great deal of debate has taken place on the origin of these chromite deposits. The chromite layers are the result of complex physical and chemical mechanisms within a primary magma chamber as it cools. The mechanisms include fractional crystallization and gravity settling. Materials which were liquid and soluble deep in the earth's crust, become solid and insoluble as the mass moves into the upper portion of the crust. In some cases, the intrusion may assimilate rock masses through which it passes, dissolving materials which may later be precipitated. The intrusion may occur as a one time phenomena, or may be the result of several intrusive phases, or pulses.

Podiform deposits evolve in much the same manner. They occur in irregular peridotite masses or peridotite-gabbro complexes of the alpine type, which are restricted to mountain belts such as the Appalachians, the Urals, and to belts that surround most of the Pacific Ocean. (USGS Professional Paper 820, p. 115)

Podiform deposits are generally younger in age than stratiform deposits.

Reserves

The table on page __ summarizes the various known world reserves of chromite.

Stratiform Deposits

The world's largest known reserves of chromite (also, vanadium and platinum group metals) are located in South Africa. The Bushveld Complex, with an areal extent of 66,000 square kilometers, or 25,000 miles, is an enormous saucer-shaped igneous complex, consisting of a central core of acidic rocks surrounded by more basic rocks. The mafic (basic) rocks cooled and solidified very slowly, thus permitting a high degree of magmatic differentiation. The final result, through the effects of gravity and fractional crystallization, was the formation of a number of distinct layers, or beds of chromite.

All of these zones, from the lowermost chromite layer upwards, are nearly parallel, roughly conforming to the attitude of the floor of the complex.

The generally accepted figure for chromite reserves in South Africa (USBM Mineral Commodity Summaries, 1983) is 2500 million short tons of shipping ore. These are high-iron chromite reserves, contained in stratiform deposits, and represent over 60% of the world's known reserves. Total world resources of chromite are estimated at 36 billion tons of shipping grade, 69% of which are located in South Africa.

The USBM estimates the identified reserves of chromite in Zimbabwe at 1100 million short tons of shipping ore. Estimates vary enormously - from 12.3 million tonnes (Duke, V.W.A, Chromium, A Mineral Commodity Review: Internal Report 86; South Africa Department of Mineral & Energy, 1981) to 564 million tonnes (International Minerals/Metals Review, 1982) Chromite occurs in the great layered intrusion of the Great Dyke, and also in discrete deposits near Selukwe. These are described as podiform deposits, but may have originally been stratiform deposits, subsequently broken up through faulting and folding.

In the United States, the Stillwater Complex in Montana contains chromite deposits of the stratiform type. See discussion on pp. ___

The stratiform deposits of the Bushveld have been dated at 2100 million years; the Great Dyke, at 2500 million years; and the Stillwater Complex, at 2700 million years.

Podiform Deposits

In the Soviet Union, almost all production of chrome ore is derived from various ultrabasic massifs in the Ural Mountains. About 90 percent of production, or more than 2.5 million tons annually, comes from mines associated with the Kemprisai massif in the South Urals (Duke, V.W.A., 1981).

Reserves of chrome in the USSR are estimated to be 16.5 million tons of shipping grade ore. The reserve estimates given by various sources are substantially different. Duke estimates the proven reserves to be 215 million tons, at an average grade of at least 40%.

Chromite deposits of Turkey are of the podiform type, occurring in alpine-type peridotite-gabbro complexes. Because of the podiform nature of the deposits, estimates of total reserves are quite different. Duke refers to estimates by Eviciman of 20.5 million tons of proven ore, plus 36.3 million tons of probable ore, averaging at least 40%. The USBM lists Turkey as having a identified reserve base of 5.5 million tons of shipping grade ore.

Discovery Methods and Exploration

Almost all of the world's known chromite deposits were found by surface prospecting and drilling in and around identified outcrops of chromite. Because of its resistance to weathering, massive chromite crops out or forms bouldery float and black sands that can be traced readily.

Extensions of layered, stratiform deposits were followed down dip, and a thorough knowledge of the structural geology of an area may aid in finding extensions which have been abruptly terminated by faulting.

Podiform deposits, and layered deposits which have been broken up by intense faulting are more difficult to locate, if they are deeply buried. A detailed knowledge of the geology of the area is essential for exploration. Magnetic and gravity geophysical techniques have been successful in identifying bodies of basic and ultrabasic rocks. Chromite, associated with magnetite, is readily identified by magnetic surveys; chromite by itself, and when associated with sulfide minerals, responds to IP surveys. However, chromite is a common accessory mineral in mafic and ultramafic rocks, and geochemical surveys have not been successful at identifying economic concentrations of chromite.

Exploration for chromite deposits must be based in large part on analogy with known chromite deposits, combined with a thorough knowledge of the geology of the area.

Although some details are obscure, the broad theory of origin of this type of chromite deposit is well known, and it is unlikely that any significant new theory will appear.

Domestic Resources/Occurrences

Stratiform Deposits

The Stillwater Complex in Montana crops out in a belt approximately 45 km long. The lithology is dominated by generally concordantly layered mafic and ultramafic rocks. There are three major zones: 1) the Basal zone; 2) the Ultramafic zone; and 3) the Upper zone. (Lambert, D.D. and Simmons, E.C., Mining Engineering, September, 1983, pp.1291-98). The PGE-rich (platinum group elements) zone, the J-M Reef, occurs about 400 meters above the top of the Ultramafic zone, and is a stratigraphic horizon approximately 2 meters thick occurring along the entire 45 km strike length of the complex. The total thickness of the zones identified exceeds 5000 meters. The cyclic units and mineralogy are comparable to the Bushveld Complex in South Africa, albeit on a smaller scale.

Podiform Deposits

Small podiform deposits containing chromite are located along the Pacific coast from Alaska to California, and along the Appalachian Mountains from Vermont to Georgia. Both areas have been affected by tectonic events.

Past Production

Both types of chromite deposits have had production in past years. The last production occurred in 1962. (USBM, IC 8895, p. 2).

The total production of chromite in the United States is about 1,850,000 long tons; of this, 950,000 tons came from Montana; the remaining 900,000 tons came from podiform deposits in Oregon, California, Pennsylvania, Maryland and Alaska. (USGS Professional Paper 820, page 112).

Greatest domestic production was during the war periods when the government subsidized production.

The U.S. Bureau of Mines compiled resource information on about 10 domestic podiform deposits. (IC 8895, 1982) These deposits contained "demonstrated" reserves of approximately 700,000 metric tons of contained Cr2O3. "Identified" reserves in these deposits are about 6 million tonnes of contained chromite. Chromite content of the deposits ranged between 5 and 25 percent. These grades are far below commercial (48%) ores.

Summary

The main identified chromite resources in the United States are concentrated in one area: the Stillwater Complex in Montana. The small podiform deposits, which occur in the northwest and eastern states, have produced small amounts of ore under war time conditions. These are relatively small deposits, even though the Cr:Fe ratio is higher than those of the chromite in the Stillwater Complex.

Irregardless of grade and Cr:Fe ratios, domestic deposits can only be mined and concentrated at costs 2 to 3 times current world prices. (USBM, IC 8895, 1982)

Other Sources

Known placer and laterite deposits containing chromium minerals are even smaller and lower grade than those of the stratiform and podiform types. Recovery of chromium from these deposits is physically difficult and very costly.

Cobalt

General

Cobalt is essential in the production of high-temperature resistant alloys, permanent magnets and high speed cutting tools.

Cobalt is a major or important constituent of approximately 70 minerals. Primary ore minerals include: linnaeite; siegenite; carrollite; and cobaltite. See table on page ___ .

Cobalt is produced primarily as a by-product of the mining and metallurgical processing of copper and nickel.

Origin

U.S.G.S. Professional Paper 820 lists seven classifications of cobalt deposits based on genetic history or type of occurrence. Of these seven, only four seem to be related to known, economic deposits.

Stratabound Deposits

More than half of the world's cobalt production is obtained from the Precambrian stratabound copper deposits of central Africa. The copper and copper-cobalt mines of Zambia and Zaire occur in a belt 500 km long and 30 km wide. The economic deposits occur in Precambrian sediments and metasediments, i.e. shales and dolomite. Reserves are estimated at over 1.5 million metric tons of metal. Grades are estimated at 0.09 to 0.45 percent cobalt (USBM Commodity Summaries, 1983)

Magmatic Sulfide Deposits

Cobalt occurs with massive and disseminated iron-nickel-copper sulfides in mafic igneous intrusive rocks. The origin of these deposits is quite similar to that of the podiform chromite deposits, i.e. a mafic/ /ultramafic magma, ascending and cooling, with the sulfides settling

World Cobalt Reserve Base

(Data in short tons of cobalt content)

Location	Reserve Base	Resources
Zaire	1,300,000	
Zambia	400,000	
Centrally Planned Economies	450,000	
Other Market Economy Countries	400,000	
United States	350,000	1,000,000
Philippines	200,000	
New Caledonia	100,000	
Morocco	50,000	
Australia	50,000	
Canada	30,000	
Finland	20,000	
Botswana	30,000	
World Total	3,400,000	8,000,000

Source: USBM Mineral Commodity Summaries, 1983, page 37

Economic Cobalt Minerals

Mineral		Percent Cobalt
Linnaeite	Co_3S_4	58.0 (theoretical)
Siegenite	$(Co,Ni)_3S_4$	20.4-26.0
Carrolite	$(Co_2Cu)S_4$	35.2-36.0
Cobaltite	$(Co,Fe)AsS$	26.0-32.4

Source: USGS Professional Paper 820, page 146 out. Major deposits of this type include the Sudbury Complex in Canada which has about 30,000 metric tons of cobalt metal in reserves. (USBM, 1983) Nickel ores at Sudbury contain 0.03 to 0.11 percent cobalt. The Noril'sk deposit in the USSR is another example of a magmatic sulfide deposit, which has been dated at about 200 million years. (Derry, D.R. 1980).

Laterite Deposits

Laterite deposits are the result of the concentration of metals by deep chemical weathering of certain ultrabasic rocks, mostly peridotites and serpentines. They occur chiefly in humid subtropical to tropical climates, or in areas where such climates prevailed in the past.

Major nickel-cobalt laterite deposits are located in Indonesia, New Caledonia, the Philippines and Cuba. Some of these deposits also contain chromite.

Hydrothermal Deposits

Hydrothermal vein and replacement type deposits are the result of the reaction of mineralizing fluids with the rocks they infuse. As a result, they precipitated ore minerals in fractures and in shear zones; or formed ore deposits by replacement of entire beds, particularly carbonates.

The high-grade cobalt veins at Bou Azzer, Morocco and the cobalt-silver-arsenide veins at Cobalt-Gowganda, Ontario are of hydrothermal origin.

Discovery Methods and Exploration

Cobalt is produced chiefly as a by-product of mining other ores, therefore, relatively little direct exploration for cobalt deposits has been undertaken.

The mines of the great copper-cobalt belt of central Africa were discovered by surface prospecting for copper.

Excepting laterites, there are no apparent problems in exploring for most types of cobalt deposits. Because of its association with copper, nickel and iron sulfide minerals, most geophysical methods can be used to detect their presence. Cobalt can be readily identified by relatively simple chemical analyses methods.

Domestic Resources/Occurrences

The Duluth Gabbro in northern Minnesota contains large, subeconomic resources of copper, nickel plus a little cobalt. The Complex, a Precambrian mafic/ultramafic intrusion, is quite similar in mineralogy to Canada's Sudbury Complex. In certain areas, the Duluth gabbro may contain 0.46 to 0.54 percent copper; 0.13 to 0.17 percent nickel; and 0.014 to 0.02 percent cobalt. Several billion tons may be available. (Watowich, S.N., Malcolm, J.B. and Parker, P.D., "A Review of the Duluth Gabbro Complex in Minnesota as a Domestic Source of Critical and Strategic Metals", presented at the SME-AIME Fall Meeting in Denver, Colorado November, 1981).

The stratiform Stillwater Complex in Montana also contains resources of copper-nickel sulfides and associated cobalt. However, the cobalt potential is small in comparison to the chromite and platinum group metals.

The Duluth and Stillwater Complexes contain the two largest known cobalt bearing magmatic sulfide deposits in the United States. The

Brady Glacier Complex in Alaska's Panhandle is quite similar, but it is thought to be considerably smaller.

Laterite deposits containing cobalt occur chiefly in California, Oregon and Washington. Very minor occurrences have been found in western North Carolina.

The Madison Lead Mine in Missouri is a very low temperature hydrothermal lead occurrence. Between 1944 and 1961, the Madison produced over 4 million tons of ore averaging 2.39 percent lead, 0.69 percent copper, 0.29 percent nickel and 0.23 percent cobalt. (Brooke, G.L., "Madison Cobalt Mine, Madison County, Missouri", a paper presented at the SME-AIME Fall Meeting in Denver, Colorado, November, 1981) The total cobalt content of this ore would supply current domestic demand for about one year. The host for this ore is the Bonneterre Dolomite of Cambrian age.

Most other Missouri lead deposits contain little, or no cobalt, so it is probable that the cobalt in the Madison ores was derived from a limited and special source, as yet undetermined. Similar, but undiscovered Madison type bodies may be present in the mid-continent area. However, their economic viability would depend on metals other than cobalt.

The Blackbird deposit, Lehmi County, Idaho, produced cobalt and copper intermittently between 1917 and 1959. Cobalt production was about 14.0 million pounds.

Some debate exists over the finer points of the deposit's geologic history. Briefly, however, the latest information (Hughes, G.J., "Basinal Setting of the Idaho Cobalt Belt Blackbird Mining District, Lemhi County, Idaho"; Proceedings of the Denver Region Exploration Geologists Society (DREGS) Symposium on The Genesis of Rocky Mountain Ore Deposits: Changes with Time and Tectonics, 1982) indicates that the copper and cobalt may have originally occurred as stratabound copper-cobalt deposits localized in a sedimentary basin of early Proterozoic age (=Precambrian). The metals were probably derived from magmatic events associated with the basin's development. Later, regional tectonic activity, and related metamorphic processes, remobilized the metals and emplaced them in their present environment.

Since 1977, the district has been intensely explored by Noranda. It is reported (Snow, G.G., personal communication, 1983) that the district may contain 20.0 to 50.0 million tons of resources containing 0.5 to 0.6 percent cobalt and about 1.2 percent copper. At recent quoted market prices of $12.00 per pound cobalt and $0.72 per pound copper, a median tonnage, i.e. 35.0 million tons deposit(s) would contain 420.0 million pounds of cobalt and 840.0 million pounds of copper, and have a gross value of approximately $5,645.0 million ($161.00 per ton).

These are impressive figures, and some people, including geologists not familiar with mining and TOTAL processing economics, would consider this to be a very important and potentially very profitable discovery.

The Chairman of Noranda has announced: "...in the light of changing economic circumstances, we have to take a pretty cold look at some of our assets." He mentionned in particular (for write-offs) Noranda's molybdenum assets, some of its copper properties, and the Blackbird cobalt property in Idaho. (Wall Street Journal, 10/26/83).

The base fact is: This mineralization cannot be mined and processed at a profit on a free market basis, in the reasonably foreseeable future. Therefore, it is not ore. The announcement, however, could be "gamemanship" in their direct subsidy strategy. Nevertheless, such statements will not give a boost to those, if any, planning domestic cobalt exploration, for Noranda is a highly regarded explorer.

Summary

It appears that North American cobalt will remain a by-product metal, and domestic resources, economically dependant on their copper and nickel content, will not be exploited without some form of subsidy or other direct incentive.

There has been considerable promotional publicity concerning the possible development of a nickel-chromium-cobalt laterite deposit in California. Despite favorable allegations, it appears to be highly unlikely that this proposed project will produce much of anything.

Manganese

General

Manganese is essential for the production of virtually all steels, and steel making and other pyrometallurgical processes are its principle uses. There appears to be no significant, satisfactory substitute for this use. Almost all raw ore is converted to ferromanganese, or silicomanganese, before final use. This value added processing is an important feature when considering the possibility of domestic manganese exploration and production.

The main ore minerals of manganese are pyrolusite; rhodocrosite; manganite and braunite. See table on page 13a . Psilomelane, mentionned

World Manganese Reserve Base

(Data in 000's short tons, gross weight)

Location	Reserve Base
USSR	2,400,000
South Africa	2,200,000
Australia	330,000
Gabon	159,000
Brazil	95,000
Other Market Economy Countries	63,000
China	50,000
India	50,000
Other Centrally Planned Economies	25,000
World Total	5,400,000

Source: USBM Mineral Commodity Summaries, 1983, page 97

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Economic Manganese Minerals

Pyrolusite	MnO_2
Rhodochrosite	$MnCO_3$
Manganite	$MnO(OH)$
Braunite	$Mn^{++}Mn_6^{+++}SiO_{12}$

Source: Glossary of Mineral Species, Michael Fleischer, 1983 throughout the literature is: A general field term for mixtures of manganese minerals, or for a botryoidal, colloform manganese oxide whose mineral composition is not specifically determined (AGI, Glossary of Geology).

The compositions of these minerals grade into one another and the exact mineralogic mixture of any particular ore is difficult to determine. The minimum economic grade of manganese ore appears to be about 20 percent manganese.

Origin

Although primary manganese deposits have been classified into three types in U.S.G.S. Professional Paper 820: sedimentary, volcanogene, and hypogene; the principal economic manganese deposits of the world are of sedimentary origin, including metamorphosed sediments. Since this report is confined to on-shore deposits, the sea floor nodules are not considered.

Manganese concentrations are ultimately a product of sedimentary processes which include weathering of a parent material, transportation and deposition in a marine environment; perhaps modified by metamorphic process or enriched by weathering.

Sedimentary Deposits

Sedimentary manganese deposits may be classified into three categories: 1) deposits associated with tuff and clastic sediments of volcanic origin; 2) deposits independent of volcanic activities; and, 3) deposits associated with iron formation. These three classes can be intergradational.

There are no known world-class manganese deposits associated with sediments composed of volcanic materials.

Sedimentary manganese deposits that are independent of volcanic processes include both carbonate and oxide minerals. The type is dependent on the environment in which the manganese was deposited: oxides in an oxidizing environment with abundant oxygen; carbonates in an intermediate to slightly reducing environment. Both environments can exist in a single depositional basin.

The important Russian districts of Nikopol and Chiatura contain flat lying or gently dipping sedimentary manganese deposits unrelated to volcanic activity. The manganese is present as oxides and carbonates. Reserves are estimated at over 2 billion tons, containing at least 20 percent manganese.

Other deposits of sedimentary origin include those in the Northern Cape Province of South Africa at Kuruman and Postmasburg, which have reserves of 300 million metric tons of ore with a manganese content exceeding 44 percent.

In Australia, manganese oxide ores are mined at Groote Eylandt, an island in the Gulf of Carpentaria, northern Australia. Reserves are estimated at about 200 million metric tons of 48 percent manganese.

Sedimentary deposits assoicated with iron formation are generally of Precambrian to early Paleozoic age. These include the deposits in Gabon; Brazil; and, the Cuyuna Range, Minnesota.

The Carajas district in Brazil, under development, is estimated to contain 60 million metric tons of ore averaging 40 percent manganese.

Different types of manganese deposition may be superimposed on one another, and the geologic history of any particular deposit may be quite complex. The highest grade ores are usually the result of oxidation and enrichment by circulating ground waters. The Moanda deposit in Gabon, has reserves of about 200 million metric tons of high-grade (50 percent) secondary oxide ore. In many, but not all such deposits, it may be presumed that the original resource of unaltered manganese carbonate at least equals the tonnage of oxide formed from it.

Discovery Methods and Exploration

So far as can be determined, all of the world's major manganese ore deposits were intially found by surface prospecting and sampling methods.

Extensions and additions have been located by drilling or other direct exploratory techniques, using elementary geologic analogy as a base. Widespread high, but quite variable, background concentrations of manganese in water, soils and rocks, makes geochemical techniques very difficult to employ.

Manganese oxides respond to induced polarization geophysics. However, carbonates offer little, or no geophysical signature.

A better understanding of the detailed sedimentary conditions which resulted in the formation of large, high grade deposits of manganese is needed. However, since there is no economic pressure to develop such knowledge, little, or nothing, is being done in the way of research.

The domestic mining industry, as a whole, is not interested in exploration for manganese because it is a relatively low unit value material of relatively specialized use. A few end users, such as United States Steel and Bethlehem Steel, have explored for manganese in foreign countries. However, they have done no domestic manganese exploration for many years.

Consumers' plants are usually "tuned" for particular sources of feed, and they are not enthusiastic about purchases from unfamiliar sources; sources which may prove unreliable, or which may contain undesirable quantities of other elements which may interfere with the plant's normal operations, or which may change the composition of their final product.

Domestic Resources/Occurrences

The major identified, subeconomic manganese resources in the United States include those at Cuyuna Range, Minnesota; Aroostook County, Maine; Artillery Peak, Arizona; and Chamberlain, South Dakota. There are other smaller deposits in Colorado, Nevada and Montana, some of which were modest producers, usually during war time.

Eight domestic manganese deposits evaluated by the U.S. Bureau of Mines (IC 8889, 1982) were found to have "demonstrated" reserves totalling 420 million metric tons with an average grade of 10 percent manganese.

According to this study, these deposits needed incentive prices ranging from $8 to almost $35 per long ton unit (22.4 pounds) of contained manganese. The very subeconomic nature of the mineralization is clearly indicated by the present market price of $1.50 per long ton unit.

Platinum Group Metals

General

The Platinum Group Metals (or Elements) include platinum, palla-

World Platinum-Group Metals Reserve Base

(Data in 000's troy ounces)

Location	Reserve Base	Resources
South Africa	970,000	
USSR	200,000	
United States	16,000	300,000
Canada	9,000	
World Total	1,200,000	3,300,000

Source: USBM Mineral Commodity Summaries, 1983, page 117 dium, iridium, osmium, rhodium and ruthenium. These are present in the earth's crust in very low concentrations: platinum, 5 parts per billion (ppb); palladium, 10 ppb; the others, 1 ppb. They occur in nature as alloys, and under some geological conditions, may occur as sulfides, arsenides and/or antimonides.

Platinum and platinum groups metals are used extensively in the control of auto emissions; as catalysts in petroleum refining; in electrical and electronic equipment manufacturing; and in jewelry.

Origin

The distribution and geochemical cycle of the platinum group metals is very poorly known.

Due to their high specific gravity, platinum group minerals are concentrated by surficial or hydrologic processes to form placer deposits, like gold.

Igneous rocks, especially the mafic/ultramafic types, contain comparatively high concentrations of the platinum group metals. These metals tend to be associated with chromium, vanadium and copper-nickel sulfides.

Except for a modest production from placers, most platinum and platinum-group metals are produced as a by-product from the mining of chromite and copper-nickle sulfide ores.

Identified world reserves are 1.2 billion troy ounces of platinum-group metals; world resources, 3.2 billion troy ounces (USBM Mineral Commodity Summaries, 1983). Over 80% of the known reserves are in South Afica.

Platinum Associated with Mafic Intrusives

Platinum metal concentrations, formed by magmatic processes, are commonly associated with sulfide minerals and with chromite segregations in mafic/ultramafic intrusions.

Deposits of this type include the Bushveld Complex in South Africa, in which the Merensky Reef, a continuous unit within the Complex, contains reserves of 159 million troy ounces of platinum. Ores now being mined from the Reef contain in excess of 0.15 troy ounce platinum per tonne. Total PGM (or PGE) content averages 0.25 ounce per tonne.

In Zimbabwe, the Great Dyke contains an estimated total of 139 million ounces of platinum in four distinct mafic complexes. Currently, there are no major platinum mining operations on the Great Dyke.

In Canada, platinum group metals are derived as by-products from nickel-copper mining in the Sudbury Complex. This is a large, layered Precambrian complex of intrusive igenous origin. Estimated resources of the entire complex are 3.4 million troy ounces of platinum and 3.6 million troy ounces of palladium.

In the USSR, the copper-nickel Noril'sk deposits are believed to account for 90 percent of total Soviet PGM production. Total estimated reserves for the USSR are 200 million troy ounces of PGM (USBM Mineral Commodity Summaries, 1983).

The Stillwater Complex in Montana is a Precambrian, layered mafic igneous intrusion which contains the bulk of the known domestic resources of platinum group metals. Major companies have announced tentative plans for production of about 30,000 to 35,000 ounces of platinum per year from this district. This would supply approximately 3 percent of current domestic requirements.

The Duluth Gabbro in Minnesota is another large, Precambrian basic intrusive complex. Platinum would be produced as a by-product of any copper-nickel mining, as it is at Canada's Sudbury mines. Estimated resources in the main mineralized area are 800,000 troy ounces.

Platinum Associated with Alkalic Intrusives

Minor quantities of PGM are also found associated with this type of intrusive. Their presence is probably the result of hydrothermal, rather than magmatic processes. Some of the large domestic copper-molybdenum mines produce platinum as a very minor by-product of their operations. This metal is usually recovered from electrolytic refinery sludge.

Platinum: Placers

Because of its high specific gravity, platinum has been concentrated by hydrologic processes, as placers, in some areas of the world.

Production from placers is not very significant in the world supply process compared to the production from mafic intrusions.

The Goodnews Bay Dredge Mine, located on the Salmon River near the Bering Sea in western Alaska, has been the largest producer of primary platinum-group metals in the United States. From 1934 to 1975, production totalled 641,000 troy ounces. The operation was closed because it was uneconomic at then prevailing prices. It has been estimated that the deposit could yield an additional 500,000 ounces at a rate of 10,000 oz/year, equivalent to 1% of domestic needs. (USBM, IC 8897, 1982).

Exploration

The AGI Glossary of Geology defines exploration as: a) The search for deposits of useful minerals or fossil fuels; prospecting. It may include geologic reconnaissance, e.g. remote sensing, photogeology, geophysical and geochemical methods, and both surface and underground investigations. b) Establishing the nature of a known mineral deposit, preparatory to development. In the sense that exploration continues beyond discovery, it is a broader term than prospecting.

In the mineral supply process, exploration is the first phase, the stimulus for which arises from demand for materials and the expectation of economic benefits when new deposits are found and exploited.

A typical exploration program evolves from a generative study that results in target identification, land acquisition, to testing and evaluation of the target(s), to definition and delineation of the deposit discovered. See Table on page __1a__; and Appendix B for an example of an exploration process chart.

Strategy is considered to be of "utmost importance" by most of those explorationists interviewed. Nevertheless, it is obvious that there is no agreed upon definition of this term as it is employed in minerals exploration. The terms: strategy, philosophy, tactics and game plan are often used interchangeably in discussion. This is basically a semantic problem. However, it has some practical effect in that many geologists employed in industry (some at high levels), have no real understanding of their employers' overall aims and goals.

Regardless of definitions, most companies employ different techniques in order to maintain or add to their mineral asset base. One

Table 6 —Typical Techniques for the Six Stages of Mineral Activity

Stages			Typical techniques
EXPLORATION	TARGET IDENTIFICATION	Regional appraisal (Stage 1)	Geologic compilation (including geophysical and geochemical data) from office files and published maps and literature. Photogeologic study of available land photographs Analysis of available remote sensing data. Field inspection from air or on the ground
		Reconnaissance of region (Stage 2)	Reconnaissance geologic mapping and sampling. Reconnaissance geochemical (stream sediments, water, soils, etc.) surveys Reconnaissance geophysical (magnetic, gravity, electromagnetic, seismic, radiometric, induced polarization, etc.) surveys (usually airborne) Reconnaissance (stratigraphic) drilling. Rapid laboratory analysis of samples. Field inspection of outcrops and anomalous areas.
	TARGET INVESTIGATION	Detailed surface investigation of target area (Stage 3)	Detailed geologic mapping and sampling Detailed geochemical surveys Detailed geophysical surveys (usually on the ground) Detailed laboratory analysis of samples. Field inspection.
		Detailed three-dimensional physical sampling of target area (Stage 4)	Drilling, logging, trenching, pitting, sinking shafts Detailed laboratory analysis of samples and amenability testing. Down-hole geophysical surveys Recovery of bulk samples and ore dressing tests. Investigation of suitability of water, land surface, and infrastructure for mine-related facilities. Feasibility and evaluation studies.
		Development (Stage 5)	Drilling to block out deposit or drilling of production wells. Construction of mine workings, plants, facilities, roads, powerlines, pipelines, townsites, etc.
		Production (Stage 6)	Operation of mine (surface, pit, or underground) or wells and related facilities.

SOURCE Adapted from similar tables prepared by Paul Bailly. See appendix C method is by direct exploration, as discussed at the beginning of this section. This method is slow, fraught with difficulties and possesses a high degree of uncertainty. Joint ventures in exploration and/or acquisition activites are common, in that the cost and risk can be shared between the associates, and geologic and geographic diversification enhanced. The other method is by acquisition, through purchase of mineral deposits or of the company that controls them. This method is usually much more costly than exploration. However, the risk is much lower, because the deposits have already been located and partially, or wholly, delineated. Processing facilities, markets, and trained staff may also be available.

Companies whose policy is one exclusively of direct exploration are vulnerable to the "law of gambler's ruin", unless they have sufficient funds to carry them through the possibility of a long run of nil results. Even then, the deposit discovered may not repay the total exploration costs.

The more successful companies have usually employed a "strategy mix", which includes direct exploration, acquisition and/or joint ventures.

Broad corporate exploration policy is supposedly guided by the nature of the corporation, and its estimatyes of future raw material requirements for its needs, or for the national or world markets.

From our interviews, and from personal industry experience, it appears that one of the most important of today's exploration decisions - what to search for in the next few years - is given much discussion and study. However, often nothing jells in the long-term, except perhaps for a few companies, like Homestake, who have consistently maintained a strong exploration search for gold. Many managements, and explorers, seem to be members of the "me, too" school of strategy. If two or three important competitors open offices in Tennessee to look for zinc, then they do too, with little cool consideration of the reason, and the long-term future of zinc.

There have been successive crazes for porphyry copper deposits in the southwest; zinc in Tennessee; Precambrian massive sulfide deposits; disseminated gold deposits in Nevada, etc.

The latest fashionable mode appears to be porphyry copper deposits in Chile, where many important explorers are actively considering production from identified porphyry deposits containing higher than domestic grades of ore.

A slightly paraphrased dictium of Von Clauswitz seems applicable: "A mistake made in the initial deployment of forces cannot be rectified during the whole course of the campaign."

The older mining companies, if left to themselves, would probably not change their long range plans and "strategy" very much. Their view of the exploration world is heavily influenced by their enormous fixed capital investment in North American smelting, refining and fabrication plants. These companies would prefer to expand the size and/or ore reserves or grades of the available feed sources. Some are participating in foreign ventures as a feedstock hedge. Others, because of the increasing foreign competition in the "older metals", e.g. copper, lead and zinc, have been forced into increasing exploration efforts for more profitable and less capital intensive metals, such as gold and silver. (Wall Street Journal, August 15, 1983).

It is thought, however, that the industry's base problems, e.g. indifferent management, poor exploration results, high cost mines, generally low grade ores, etc., will gradually force miners to engage in more diversification, both vertically and horizontally. There will be more money spent in "safe" foreign countries, directly and through joint ventures with some government agency of the host country, e.g. Codelco-Chile.

Most major oil companies have employed the two differing basic policies for mineral acquisition: direct entry through self-managed minerals exploration; and, indirect entry through acquisition of existing mining companies and their operations, exploration staff and know how.

This activity is similar to the policies of mining companies who must decide on either acquisition or exploration for mineral properties. Oil companies have an advantage in being cash rich.

However, historically, many oil companies have not been comfortable with the very long-term requirements of mineral exploration and development. Mineral exploration is risky, and slow; mineral market prices more critical; and mineral projects typically have longer payout times than do oil and gas ventures. (S. Muessig, Getty Oil Company, personal communication, 1983). Exploration and development for minerals are greatly different from that for oil and gas. These suddenly perceived differences are one of the principal reasons behind "big oils'" general disenchantment with the non-fuel minerals business. One wonders why these facts were not considered before their entry into the minerals field.

The size of the strategic materials market precludes much interest being shown by any of the major mining or oil groups, except under very special circumstances. Identified resources, such as the platinum group metals in the Stillwater Complex in Montana, are a minor exception. ARCO acquired a land position there when they purchased Anaconda. They are now trying to realize on this old asset.

According to Crowson (1982), in 1980, the United States consumed, in gross purchased value, the following approximate amounts of the selected strategic metals: manganese, $240.0 million; chromium, $290.0 million; cobalt, $475.0 million.

Even if a large mining or oil company could obtain a 33 percent share of the market of one or more of these metals, the gross sales and resultant return on their investment would not be financially significant in the context of their usual business. The very few "small" or "medium" sized mining companies will not be interested because of the very high financial risk involved. They would run a substantial risk of total corporate failure.

Cobalt and platinum group metals are, or may be produced as by-, or co-products of the mining of nickel and other ores. It is customary to evaluate such mining investments on the major, familiar contained metals. An opportunity whose economic viability depended on cobalt prices, for example, would receive a very cold eye from those asked to finance the investment. They may be willing to gamble on, say, future nickel-copper prices, but not on cobalt.

The historic record exhibits many examples of failures of those operations dependent, like that proposed by Ni-Cal Development on a California laterite deposit, on the sale of all possible mineral products (Ni, Cr, Co, Mg, etc.) in the ore. If one link in the chain is broken, the whole enterprise collapses.

Examples

There has been no new, significant discovery, indeed no substantial search for most strategic materials in the United States for decades. Except for exploration on known resources of platinum group metals, there are no specific examples of recent strategic metals/materials exploration/discovery which could be described. This statement is based on personal experience and the interviews.

The general principles involved, however, are the same for all types of metal exploration, so the following examples of non-strategic minerals exploration are illustrative.

Crandon

The Crandon deposit in Wisconsin was discovered in 1975 by Exxon Minerals. It is one of the largest deposits of its type ever found in the western hemisphere. The deposit is a massive volcanogenic sulfide body in metamorphosed rocks of the Precambrian Canadian Shield. It is buried under only about 60 meters (200 feet) of glacial debris. The broad area was selected by Exxon for its overall geologic favorability, and an airborne electromagnetic geophysical survey was carried out over an area of approximately 5,000 square kilometers (2,000 square miles). Twenty-five anomalies were detected by the survey and classified by the geophysicists as anomalous. The Crandon anomaly was rated 24th, because it was "too long and too weak", and was probably a result of "cultural effect". This illustrates the problem of geophysical interpretation nicely, for none of the higher rated anomalies contained significant mineralization of any type.

The geologists in Exxon's north central office has actually received notice of office closure and transfer before anomaly 24 was tested. The whole program was somewhat over budget, and the geologist in charge had to scratch around to find money for the initial drilling which led to the discovery. "Luck" was seemingly involved.

The deposit is not fully delineated, but may contain 68 million tonnes (76 million short tons) of 1.4 percent copper, 5.8 percent zinc, 0.5 percent lead, 1.2 ounces silver and 0.018 ounce of gold per ton.

The actual cost of the initial discovery was about $2.75 million. Perhaps another $22 million has been spent in drilling, land, environment, legal, etc., for a total, including overhead, of something over $30.0 million.

At recent prices of $0.75/pound copper, $0.20/pound lead, $0.40/ pound zinc, $400/ounce gold and $12/ounce silver, the deposit has a gross in-place value of about $92 per ton, or $7,000 million. For a production rate of 3.50 million tons per year (10,000 tpd), it would require a capital investment of at least $220.0 million to place this deposit in production. At the given metal prices, after smelting charges, such an operation MIGHT breakeven and return production related capital.

A very substantial increase in the State tax rate applied to mining, made after the announcement of the discovery, deleteriously affected the economics of the project. This action, now partially modified, strongly assisted in moving the project from "probably viable", to "possibly" sometime in the future.

We have private information that in the last 15 years, Exxon Minerals has spent in excess of $350.0 million for minerals exploration in the United States. This figure does not include mine purchases or exploration in foreign countries. The only significant (Exxon's context) results of their domestic exploration efforts are Crandon, and a large molybdenum porphyry deposit in Nevada which will not be economic for another ten or fifteen years. Funds, if any, derived from the latter deposit, will be received so far in the future that their present value is minscule, and can be ignored for economic analysis.

Although the exploration costs are "sunk", in accounting parlance, in a practical exploration/reward sense, Crandon cost $350.0 million to find. If normal engineering economic principles are applied, it can be easily shown that the deposit will never repay its "front load", interest charges on this load, and its capital.

Some geologists, but not financial people, will quarrel with this statement. However, the cost-benefit reward to explorers cannot be calculated on a parochial basis. Each dollar spent for exploration must return, with interest. If not, then the loss must be carried by other segments of the business, the funds of which are also at risk. Just because unsuccessful exploration funding can be written off, does not mean they weren't actual cash outlays. If Exxon had started with $350.0 million, and had NO OTHER SOURCE OF INCOME, they would now be out of business.

The senior author, when managing the minerals group of the largest domestic independent oil company, was privy to many discussions of this whole subject with senior management, investment bankers and other money masters. All would agree agree with his position.

R.C. Burns, a high official of Consolidated Gold Fields of London, has said: "Successful investment in mineral exploration requires a continuous flow of discoveries whose subsequent exploitation provides a satisfactory return on the TOTAL investment." (emphasis added)

Exploration managers do not like this treatment, because it often casts a spotlight on just how expensive and fruitless their "non-result" activities have been.

Exxon Minerals, in the last two years, has reduced its professional staff from 167 to 60 people. Average expenditure per professional employee was approximately $0.350 million per year.

This is a fairly typical profile of the results of modern scientific base metal exploration in the United States.

Speculation

On a speculative basis, one wonders what Exxon's domestic exploration results would have been if the $350.0 million had been spent in a different fashion. Say: airborne electromagnetic surveys, $25.0 million; land, $50.0 million; geologic service (minimum nature), $25.0 million; administration, etc., $75.0 million, for a total of $175.0 million The remaining $175.0 million, if applied to drilling, at $30/foot, would have paid for 5.5 million feet of drill hole.

We suspect, but cannot demonstrate without further work, that this much drilling, directed semi-randomly, in SELECT, not randomly chosen favorable mineralized areas, would have produced better results.

The implications are obvious. A comprehensive study of this possibility would be desirable and of great interest to explorers, mineral policy makers and government organizations.

Homestake Mining's Exploration Program

One of the better, successful modern exploration programs led to the discovery, by Homestake Mining, of a large gold ore deposit in an area not previously known to contain gold.

The following statements have been summarized from a paper presented by James A. Anderson at the American Mining Congress Convention in Denver on September 30, 1981. For full text, see Appendix C.

Higher, free market gold prices provided strong incentive for Homestake's management to commit to a long-term, definite and planned exploration program for gold. In 1978, management agreed to fund the program at $12.0 million a year, for at least five years. At the time, corporate profit was $31.0 million, so some business courage was required.

The exploration program was based on newly developed geologic concepts (not revealed), basically derived from special analogue modelling; probability analyses, mainly based on in-house data; and a firm and fundamental view of the purpose of exploration, which is the location of ore, not "targets".

The program had definite, quantified goals: 1) discovery of a major, 3.0 million ounce gold deposit in no more than ten years; 2) a 1.5 million ounce gold deposit within five years; and 3) reserves containing 0.5 million ounces as "fall-outs". In addition, the deposits were required to be suitable for large scale mining, with open pit grades exceeding 0.15 ounce gold per ton and underground mining grades exceeding 0.30 ounce gold per ton.

Prospects whose estimated potential did not meet these firm criteria were ruthlessly discarded. We believe these definite, quantified parameters are one of the most important factors whcih contributed to the success of the program.

Costs and estimated success ratios were derived from in-house records, published information and privately developed data. These were used to arrange a statistical basis for cost/success expectations.

The exploration organization was reorganized in order to operate and manage by function, rather than by geographic location, the customary, perhaps outdated, method.

The program achieved success in two years. An economic open pit deposit containing at least 3.3 million ounces of gold was found in the fall of 1980. The discovery may be fortuitous, however, it is difficult to quarrel with success.

This is a very interesting and important case and the full text of of Mr. Anderson's paper deserves careful study.

Current Exploration Technology and Methodology

Geochemistry

The term, geochemistry, in its broad aspects, also includes geobotany, rock analysis, assaying, etc.

Geochemical prospecting is based on the knowledge that an envelope, or halo, of trace primary mineralization is likely to occur around a near surface economic mineral deposit, and that a secondary dispersal pattern of the element(s) sought, may be created by the weathering and erosion of the deposit.

These primary envelopes and secondary dispersions contain higher than average concentrations of the element(s) sought. If these anomalies are pronounced enough, they give much broader indications of possible mineralization than the deposit itself.

The size and strength of these anomalies depend upon the element(s) sought, the type of the deposit, and on the scale of the sampling program.

Anomalies range in size from hundreds of square kilometers to a few hundred square meters. Reconnaissance, or regional screening programs, produce the largest anomalies. Results of this initial work are used to guide and focus effort upon "anomalies within anomalies". These screening steps may be repeated several times, in order to identify the highest anomalies associated with favorable geologic conditions.

The materials commonly sampled are water, recent sediments, soils, rock or vegetation, separately, or in various combinations. The choices are guided by mineralogic, geologic, topographic and climatic conditions.

Samples may range in size from 0.1 grams to several kilograms. Again, the choice is related to the element(s) sought and to the material(s) being sampled. The sampling process has the greatest potential of error in the whole system.

Analytical techniques range through the whole gamut of analytical chemistry. However, various wet chemical techniques are commonly employed. For base metal exploration, three or four elemental determinations are usually made on each sample.

For some metals, like gold, because of its nonsolubility, recourse may be made to analyses for commonly associated elements, e.g. arsenic, antimony, mercury.

Manganese and chromite ore minerals are usually associated with magnesium, iron and aluminum minerals. These elements are so ubiquitous that they cannot be used as pathfinders.

Cobalt, in sulfide deposits, is sometimes associated with arsenic, antimony, copper, nickel and silver.

Analytical results are commonly plotted and contoured in a fashion similar to elevations in topographic mapping, and detailed geologic and other exploration work is concentrated on the highs.

In recent years, sophisticated computerized statistical trend surface analysis of the resultant data has been intensely applied to interpretation. The U.S. Geological Survey has been a leader in this field.

Geochemical exploration is one of the basic tools of modern mineral exploration. It is relatively rapid, cheap and direct, in that the concentrations of the metal(s) sought are looked for directly, not through their electromagnetic analogues.

Nevertheless, geochemical exploration has many unsolved problems which limit its effectiveness. "Background noise" in the form of man-made anomalies is almost omnipresent. (Long abandoned, century old ore haulage roads have been detected!)

Large areas of favorable ground are partially or wholly covered by post-ore rock and/or sediments. In such cases, geochemistry cannot be employed, except in very exceptional circumstances.

Despite the sophisticated interpretation methods, problems abound. For example, a small mineralized body at, or near the present surface may provide a much stronger and larger anomaly than a substantially greater body at modest depths. In fact, the latter may produce no detectable geochemical "signature" at the surface whatsoever.

Geophysics

Geophysical techniques are one of the primary screening tools of mineral exploration. Despite this statement, it is apparent that there is substantial disenchantment with both the costs and the results of geophysical programs.

Magnetics

This includes airborne, ground and borehole methods. Except for a few specific minerals, e.g. magnetite, pyrrhotite, etc., magnetometer surveys are of only indirect use in searches for economic minerals.

Almost all types of rock have some magnetic properties. These properties are controlled by the amount of magnetic material present, and by the earth's natural magnetic fields, which induce magnetism in rocks. Modern instrumentation can detect rather minor differences in the magnetic "print" of varying rock types.

Magnetic surveys do provide important indications of lithologic contrasts, faults, folds and other gross geologic features. When properly interpreted, magnetometer surveys offer a method to roughly analyse older rock "surfaces" covered by younger rocks. Magnetometer surveys are relatively cheap and rapid to produce. In areas where geologic conditions are fairly well known, interpretation can be relatively simple. In "frontier" areas, interpretation may be quite difficult.

Electromagnetics

This includes airborne, surface and borehole methods; AFMAG, TUREM, DIGHEM, etc. which are acronyms for various patented methods and techniques; self-potential, induced polarization, etc. All electromagnetic techniques measure the flow of electric currents, natural or man-induced, in the earth's crust. Perceived distortions in the postulated pattern of flow of these currents are considered to be "anomalous". Since metallic mineral deposits are usually much more conductive than their enclosing wall rock, they often create "anomalies" in measured current flows. Anomalies have to be interpreted in terms of the assumed geologic and mineralogic conditions prevailing in the area explored.

Anomalies are basically appraised by analogue comparison to theoretical models, and the size, shape and depth of the object required to create the particular electromagnetic signature is computed. These theoretical targets are also secondarily appraised by empricial comparison to the known geological and mineralogical characteristics of the area surveyed, and to known mineral deposits of the type sought.

Radiometrics

Gamma radiation is emitted by radioactive elements in the earth's crust. Besides the uranium-thorium series, these include potassium, an important constituent of many minerals in igneous rocks.

Airborne and surface based instruments can detect and discriminate between various sources of radioactivity. Rarely, the radioactive element may be associated with a base or strategic metal. In this case, radiometric surveying may be of indirect use in exploration for such metals.

Concentrations of potassium, sometimes contained in the rock alteration zones adjacent to certain types of ore deposits, can also be detected.

Gamma radiation, however, is completely absorbed by about 60 centimeters of soil or rock; and, "background noise", in the form of cosmic radiation, is ubiquitous. These factors ordinarily preclude the usage of radiometric surveys in exploration for elements other than the uranium series.

Gravimetrics

This includes surface and borehole. This method, long employed by the oil industry, has only limited use in base or strategic metal exploration. The instrument detects and measures lateral variations in the earth's gravitational field that are associated with near-surface changes in rock density. "Background noise" is severe and the data must b be carefully adjusted and interpreted.

It is mainly employed in regional geologic mapping, where it may give some information on large, buried rock masses whose density differs from the surrounding rock.

On occasion, it is also employed as a follow-up, or supporting function, in the interpretation of other types of geophysical anomalies.

The technique has been used to search for chromite in areas containing known podiform chromite masses. However, its cost, limited depth" penetration and data interpretative difficulties have restricted this use.

Seismic

Reflection and refraction seismic methods yield information on the differences in the elastic properties of the rock being tested. These properties control the velocity at which sound energy is transferred through the rock. The initial sound wave is provided by explosives, drop weights, etc. The data acquired can be digitized, and quite an accurate third dimensional picture derived.

Seismic surveying has only limited use in mineral exploration, because most of the targets are small, compared to hydrocarbon bearing structures; and their geometric configurations are often not essentially horizontal as are most hydrocarbon deposits.

Good seismic interpretation requires a substantially accurate knowledge of the subsurface geology of the area being surveyed. The mineral explorationist does not usually have this knowledge.

Earth Satellite

Despite the publicity put forward by its mostly vested interest proponents, few, if any, explorers seriously use, and none currently rely upon, data collected by earth satellite techniques.

Satellite imagery has been useful in providing regional geologic structural information in relatively unexplored and forested areas. Its multispectral scanning capabilities also provide some information on the chemical composition of the earth's surface and of the vegetative cover of the area examined. "Several important technical and geological limitations must be recognized, however, in structural analyses using MSS images." "Landsat 4 Thematic Mapper (TM) images, which include two new spectral channels, provide means of reducing the (lithologic) ambiguities, thereby resulting in a more efficient method for mapping hydrothermally altered rocks. Higher spectral resolution is needed, however, for mineral identification." (Rowan, L.C., Research Geologist, USGS, "Satellite Technology Updated", a paper presented at the American Mining Congress Convention, September 14, 1983).

However, at present, the data supplied is much too generalized for most direct mineral exploration work. This is particularly true in areas like North America where regional geologic settings are well known.

Attempting to integrate satellite data with other geologic, geochemical and geophysical information, will create interpretation problems of enormous complexity. Some of those interviewed thought a generation would be required to develop true understanding. A few thought that mineral exploration applications could develop within the next few years. Practically, it appears that satellite imagery may be of more benefit in exploration in foreign countries than it will be in the U.S. Countries with large, relatively unexplored areas, e.g. Australia, Brazil, parts of Africa, etc. Most of the mineral lands in these areas and countries have not yet been affected by the impediments associated with North American society, and the data generated may be put to use.

The geophysicists interviewed noted that it is quite difficult enough to interpret data collected 150 meters or so above a specific target, without stretching the distance to several hundred kilometers. Again, we are searching, at the best, only 150 meters or so into the earth's crust, large areas of which are covered by post-mineralization cover. Satellite geologic data does not appear to be the explorationists' panacea.

Aerial Photography and Photogeology

Aerial photography in color, or black and white, allows the geologist to obtain synoptic views of selected areas at almost any scale. The photographs are used as "base maps" for field work and photogeologic studies. After spot field investigations, quite accurate base geologic and topographic maps can be prepared, for some terrains, at a relatively small cost. Photography of areas covered by dense conifer vegetation, or those with very high topographic relief, is not very effective.

Explorers commonly employ private contractors for aerial coverage of small "target" areas. For regional work, they usually rely on photos supplied by government agencies, e.g. U.S.G.S., Forest Service, etc.

Photogeology is a useful exploration tool, nevertheless, as the available information derived from it gets a wider and wider "circulation", its primary importance declines.

SLAR

This is an acronym for Side Looking Radar Photography. This technique has provided some help to those exploring in densely forested areas, e.g. South America, Africa. The radar signals penetrate vegetative cover, are reflected from rock and soil, and are photographed on the radar screen.

This technique, in effect, "strips" the vegetative cover from the surface, allowing photogeologic interpretative techniques to be applied. Combined with a little spot field checking, this allows the interpreter to produce reasonably accurate, gross geologic maps containing structural and rock type data, suitable for reconnaissance work.

Geophysics Summary

Of the techniques described, magnetics and electromagnetics are the methods most frequently used in minerals exploration.

All of those interviewed agreed that current geophysical exploration techniques are in general, only probing to depths of about 150 meters (500 feet) below the surface.

Most thought that some of these geophysical techniques are approaching limitations set by physical laws of nature. In particular, the decline of signal strengths by the "inverse square of the distance" effect.

This limitation can be partially alleviated by moving the geophysical instruments deeper into the earth's crust via boreholes. Both "sender" and "receiver" can be thus placed, and greater volumes of rock screened. In some cases, more efficient instrumentation could effectively double the volume of rock being searched.

Some of the present techniques can be employed in boreholes. However, considerable improvement is still required in instrumentation, and in interpretation of the data collected.

"Background noise", mostly man-made, is becoming a very serious problem as the population moves further into the countryside. Such diverse items as ultrahigh-voltage power lines, electrocathodic metal protection and, "transient currents" were described as being serious handicaps to geophysical exploration and to its related data interpretation.

A large majority of all those interviewed agreed that all data collection techniques were far ahead of data interpretation and its final analysis. The authors agree, as do most other pragmatic explorationists. Academics and geotheoreticians appear somewhat doubtful. However, few of their interpretations get tested by the drill rig.

The common employment of mini-computers has enabled geophysicists to manipulate data in "real time", and in ways not possible a few years ago. Despite this apparent advantage, most explorers are conscious of the fact that "if you don't really understand what you are manipulating, it doesn't help to do it faster."

Almost all of North America's known favorable geologic environments, assumed suitable for base metal occurrences, have been covered by one or more airborne geophysical surveys. The introduction of each new, allegedly better, geophysical technique or instrument has replicated coverage in many areas.

Most of the airborne electromagnetic coverage is corporate and proprietary. After more or less select use of each survey, the collected data is filed and usually forgotten.

It is probably fair to say that almost every geophysically detectable base metal ore body in the United States has been found - in the geophysical sense. These lie, physically unidentified, in semi-dead files, because of interpretation problems, and the explorers' mental attitudes.

Since no practicing geophysicist seems to expect the development of any substantially significant new technique, these "file bound" ore bodies must await a broad gauged advance in geophysical interpretation. New instrumentation and technique are of little use if interpretation lags, as it does now.

Interpretation is THE geophysical problem.

Strategic Materials

There has been little interest in strategic material exploration for a long period of time, and since chromite and economic manganese minerals cannot be detected by airborne electromagnetic methods, there has been little, or no, airborne coverage of their environments.

Recoverable concentrations of cobalt and platinum group metals are commonly associated with nickel and iron sulfide minerals. Under certain conditions, the latter can, and have been detected by airborne electromagnetic methods.

Some manganese ore minerals and chromite can be detected by some surface geophysical techniques. The best method appears to be induced polarization (IP). This technique was developed for porphyry copper exploration. In this method, a measured electric current is introduced into the earth via electrodes. If this current is suddenly interrupted, an electric potential can be measured between the electrodes for some time after the current flow ceases.

In effect, some minerals, under certain conditions, act as batteries. Their discharge, after current flow is interrupted, can be measured by I.P. instrumentation.

As in most geophysical techniques, interpretative uncertainties abound. In addition to sulfide, manganese and chromium minerals, IP effects are produced by graphite, magnetite, ilmenite, certain clays and other minerals. In fact, many IP anomalies have no ascertainable cause whatsoever.

The U.S.G.S. is doing some research work on the application of geophysical methods for the location of chromite deposits. (Wynn, J.C., Mining Engineering, March 1983, pp.246-251) Their initial work is of scientific interest, even though it is probably site specific and costly. However, unless a possible economic reward can be firmly demonstrated, no substantial exploration group will carry these clues any further.

Drilling

Drilling is the ULTIMATE TEST of all explorationists' theory, technology and methodology, for all mineral commodities, including ferrous, non-ferrous, industrial minerals, and oil and gas.

There is a universal desire for substantially (at least 30%) lower exploratory drilling costs. A large number of those interviewed brought uop this subject voluntarily. Drilling costs, direct and indirect, are one of the most significant limiting factors in mineral exploration today.

There are two main methods of mineral exploration drilling: core and rotary. Diamond core drilling physically removes a cylindrical sample of the rock, which, depending on size, may be 27-150 mm (1-6 in) in diameter and 3 or more meters long (approx. 10 ft.)

Rotary drilling crushes, grinds and chips the rock, by means of a toothed bit, so that only cuttings of the rock penetrated are removed by water or air, for analysis.

Core drilling is preferred in order to obtain accurate samples for core logging and assaying. Today, costs for diamond core drilling usually range between $80-$130/meter ($25-$45/ft). This includes contractor's cost, site preparation, assaying and geologic logging. Costs are also related to size and depth of hole, rock type and geographic location. Usually, rotary drilling costs range between $32-$80/meter ($10-$25/ft), again, dependent on the size of the hole, method of drilling, type of rock and location. Rotary drill holes for oil have reached depths of 10,000 meters. The deepest core hole in the U.S. is about 2400 meters.

Today, mineral exploration companies are drilling to an average depth of roughly 530 meters. Ten years ago, the average exploratory hole was approximately 360 meters (J. Power, Longyear, personal communication, 1983) This is a compound rate of increase in depth of about 4% per year.

In the last two years, contractors' diamond drill costs have declined about 30 percent (A.P. Wicklund, Manager, Drilling Operations, AMAX, personal communication, 1983). The two main factors that brought this about were lower diamond prices, and breakeven bids for survival. Diamond prices are now rising again, so this temporary cost relief will vanish.

The American minerals drilling industry, unlike their Canadian counterpart, provides no published statistics on drilling. It is estimated, however, that mineral exploratory drill costs have risen at least 75 percent per unit in the last 10 years. When this increase is coupled with average drill hole depth, it is obvious why cheaper drilling is in such great demand.

The Pennsylvania State University and the Society of Economic Geologists are attempting to provide historical and on-going compilation of mineral exploration related drilling statistics. Both are well intentioned organizations. Frankly, however, we feel that no one should place much reliance on the accuracy of, or time of delivery of, their data. These groups will be dependent upon voluntary disclosure of the information sought. Several scores, if not hundreds, of mining and drilling companies have disappeared within the last 3 decades. Their drilling data is gone forever, and limited, or select, samples of data will also be of limited value.

Cheaper drilling methods would allow the testing of more targets, however identified and defined. This would assist in bettering the current ore discovery rates of the exploration industry.

Diamond drilling techniques used today are not greatly different from those used in the 1860's when it was first employed for coal exploration in Pennsylvania.

There has been a steady, but very slow, incremental increase in the overall technology of this method. However, there have only been two significant improvements in the last 3 decades. The first was the introduction of wireline drilling; the second, the advent of impregnated diamond drill bits.

Rotary drilling techniques, for metals, have also stabilized at a modest technologic level. Sampling related problems prevent rotary drilling from being employed to a much greater extent in minerals exploration.

There has been comparatively little direct research of any importance applied to MINERAL EXPLORATION DRILLING and its problems.

The U.S. Bureau of Mines and a drill machine manufacturer and contract drilling company. E.J. Longyear, have jointly designed a method for replacing worn diamond bits without removing the drill rods from the hole, a costly and time consuming operation. However, with the advent of impregnated diamond bits, it has proven more cost effective to stay in the hole with these longer wearing bits, than it is to purchase the relatively expensive equipment required to change the now semi-obsolete surface set bits.

Most, if not all, of the incremental improvements have been obtained as spin-offs from oil drilling. These have been helpful. However, due to various factors, e.g. size of target, rock types, dimensions of drill holes, plus a limited market, etc., much oil industry drilling technology and methodology has not, or cannot, be adapted to mineral exploration.

No really significant changes loom on the horizon. It appears clear that substantial technical and cost benefits would probably flow from a long-term, well conceived and funded research program in mineral exploration drilling techniques.

The Future

Future Requirements/Developments in Exploration Technology

Geochemistry

Geochemistry needs faster, more accurate, more sensitive and more specific analytical techniques.

The ideal methodology would consist of "hands-off", automated sample preparation and whole-rock, accurate, multi-element analyses; all performed on a completely automated basis in real time. Current practice in sample preparation is a multi-stage procedure consisting of crushing, grinding, pulverizing and selection of a sample of appropriate size; each stage of this process offers opportunity for error. A completely automated, self-checking procedure would eliminate most of the present potential for error.

A majority of explorers, even the largest, send their samples to outside laboratories. Most of these do good work. Nevertheless, there is, fairly commonly, enough error and bias in reported results, to cause interpretation and confidence problems.

At times of great interest in certain metals, like gold at the moment, good laboratories may have a 4 to 6 weeks' backlog of samples to be analysed. Such a situation often causes immense and expensive problems in drilling, for the drilling pattern is guided by previous results.

An instrument is also needed which will analyse drill hole derived samples, at least semi-quantitatively, on site. Preferably the technique would not alter the physical characteristic of the sample. The analytical methodology of the future should be accurate, non-destructive, and possess in-situ capability.

Accurate multi-element analysis is greatly desirable, no matter what type of sample is being analysed. It is a statistical certainty that potentially valuable deposits of element "x" have been overlooked because analytical work was concentrated on elements "y" and "z". This is particularly true if the mineral containing element "x" is rare, or is physically difficult to identify by commonly employed methods.

Even if there is no potential economic element present, it would be of great geologic value to be able to identify and quantify all of the "trace elements" associated with particular types of mineralized bodies. In time, the "patterns" obtained may offer definite clues to the presence or absence of economic mineralization.

Borehole and handheld instruments, employing X-ray fluorescence analysis methodology, have recently been developed. These are specific for such elements as silver, gold, molybdenum, tin, etc., and show promise. However, substantial improvements in sensitivity and analysis reproducibility are needed. ICP (Inductively Coupled Plasma atomic emission spectrometry) is the latest technique, claimed to be a multi-element analytical tool. There are, however, substantial problems with inter-element interference and element detection levels.

High precision and sensitive analytical methods, e.g. ICP, neutron activation, laser bombardment, irradiation by radioactive isotopes, etc., have only limited use in geochemical work because of their high unit costs (more than $50 per sample) and certain physical limitations of the equipment.

No matter what analytical techniques are employed, and how many elements determined, the limiting factor in today's or tomorrow's exploration geochemistry appears to be the interpretation of the results obtained.

Like exploration geophysics, exploration geochemistry delivers vast amounts of data that no one truly understands. Fully integrating this information with data from other exploration techniques, i.e. geology and geophysics, is currently very difficult. An extremely few "seat-of-the-pants" ore finders, may perhaps, be able to do this at some intuitive level. However, not the ordinary explorationist.

Geophysics

Geophysical exploration techniques, particularly the electromagnetic methods, should be more discriminatory.

At present, the various methods available cannot certainly distinguish between anomalies caused by, for example, pyrite, chalcopyrite or graphite. In fact, the cause of many geophysical anomalies cannot be definitely determined, even after drilling.

Some large explorers have research programs aimed at developing instrumentation which will discriminate between various minerals, particularly sulfides. This work is proprietary, and very little factual information is available. The geophysicists interviewed thought that such developments would not be realized before the end of the century, and even then, would only compound the interpretation problems which already exist.

Furthermore, since ground geophysical techniques are normally applied only after land acquisition, no exploration manager is going to walk away from an anomaly simply because an instrument reported "pyrite, not chalcopyrite".

Electronically, instrumentation needs advances in screening out natural or man-made "background noises". This improvement in signal/ noise ratio would, perhaps, somewhat increase the effective depth penetration of the technique.

Instrumentation also needs additional miniaturization and improvement for borehole use.

There are no very special geophysical problems related to strategic materials that are susceptible to change. Any improvements in instrumentation and technique will be of some benefit to strategic metal exploration. For example, an effective borehole IP transmitter and receiver, would perhaps, be effective in exploration for podiform chromite bodies, in areas where they are known to occur.

All geophysicists secretly yearn for the "black box" which will say - drill here! - eliminating the geologists. This day is far removed.

The single biggest geophysical problem is data interpretation. A substantial improvement in this "art" would far outweigh any current or expected improvement in technology. Much more practical, i.e. field research, is required. Explorers do not perform much "post mortem" work.

One of those interviewed stated: "Better instrumentation is like giving an encyclopedia to an illiterate - the pictures are nice, but it doesn't help him to read."

Research and Development

Mineral exploration technology and methodology have not been the subject of significant research and development attention for some time. Current metal market prices and other problems have resulted in reduction of previous modest funding levels.

It is difficult to obtain a realistic grasp of the mineral exploration related R&D. Most work is spread throughout academia (geology); the U.S.G.S. (geology, geophysics and geochemistry); the U.S. Bureau of Mines (drilling, geophysics, miscellaneous); mining and oil companies (geology, geophysics and geochemistry). Equipment manufacturers, with a few exceptions, mainly among geophysical contractors, do very little R&D, since their markets are quite limited.

There appears to be no reliable figure available for the amount of direct exploration related R&D monies expended for any specific period of time. "Guesstimates" range between $10 and $50 million per year (North America), excluding federally funded activities.

To compound the quantification problem, there is no agreed upon definition of work that should be classified as mineral exploration R&D.

Is a U.S.G.S. geologist studying the magnesium content of chromites engaged in mineral exploration research? Most practicing explorationists would say no; but there is definite justification for argument.

One thing does appear clear, however. Exploration R&D, no matter how defined, is, by comparison to most other technical fields, very poorly funded and directed.

Geophysical and geochemical instrumentation are being slightly improved by enhanced electronic circuits; small computers are more common; and interpretation techniques receive constant tinkering.

If any potential order of magnitude advance is being worked on in laboratories, no expert will acknowledge it. The only possible exception may be United Nuclear's MAP (Metals Analysis Probe) which was introduced early in 1983 for silver analysis. This is an x-ray fluorescence analysis technique, using a hand-held digitized instrument, which is element specific. It could possibly be modified to cover a wider range of elements and its sensitivity improved.

Mineral explorers are a curious lot. Although in a "gambling" business, they generally view new, allegedly important, technical developments with a cold eye. "Let others prove it first" is the initial reaction.

Analysis of the Mineral Exploration Industry

The chief, non-technical barriers to American base and strategic metal exploration today are:

1. the generally low prices of most metals, and
2. their rapidly fluctuating price cycles, which preclude assured, long-term planning;
3. the enormously increased (since 1970) capital requirements per unit of thruput, for fixed plant investment;
4. the fact that these very large capital charges require bigger and/or higher grade ore deposits, with metal prices in higher real terms, in order to amortize the initial investment;
5. large, high grade ore deposits are very rare in nature, so greater amounts of time and money must be invested in the search for them - at a much higher exploration risk.

The effect of the five items listed above are compounded by the domestic exploration industry's poor discovery rate, using current technology and methodology. The chance that any particular prospect is an ore deposit is about 1 in 100. For a "world-class" ore body, the chance may be 1 in 1000.

It should be clearly kept in mind that the sole purpose of mineral exploration is to find economic mineral reserves, i.e. ORE, not sub-economic resources! Exploration management and success should be judged by this criterion, not by the number of "targets identified", or "near misses", or "good possibility zones", or whatever the latest non-success euphemism turns out to be. (for additonal comments, see Parrish, I.S., Mining Engineering, November, 1983, pp.1531-33)

Most explorers are pessimistic about the future. They foresee more government interference and "control", increasingly expensive exploration, more foreign competition in metal production, and, in general, no order of magnitude "breakthrough" in mineral exploration technology.

A negative "mind set" often becomes self-perpetuating, and is certainly not inducive to bold and vigorous mineral exploration activity. However, it is very difficult to be "bold and vigorous" when one is hemmed in by: a surplus of some metals, adverse governmental actions, over enthusiastic environmentalists, land access problems, poor corporate management, etc., etc.

There will be no easy exit from this cage of folly.

Another fundamental problem: the American mineral industry is being asked to provide more and more minerals from less and less land, the basic raw material of exploration.

Assuming we had an almost absolute knowledge of the physical laws of ore deposits and much better exploration technology, it would still be of little practical use to determine that a major, economic deposit of chromite, for example, should lie under a Baltimore suburb; or

Portland, Oregon; or, Glacier National Park; or wherever.

None of those interviewed were very excited about any direct incentives for mineral exploration. "The government giveth and the government taketh away" typifies the prevalent mood. Smaller, perhaps less competent groups, will no doubt eagerly grasp for subsidy money, with doubtful benefit to the taxpayer.

It is possible, however, that in certain cases, an adjustment of current tax depletion allowances would provide an exploration incentive at little, or no, dimunition of federal government revenues.

Cobalt, for example, currently has the same percentage tax depletion rate (22 percent) as lead, zinc, molybdenum and many other much more common, but much less strategic materials.

Again, for example only, there are known, currently unexploited copper-cobalt resources in Lehmi County, Idaho. In part, they remain unexploited because of low copper prices and wildly fluctuating cobalt prices (see p. 12).

At some increased percentage tax depletion rate for cobalt and perhaps, the associated copper, these deposits would probably be economic in the near term.

Currently, the federal government and the nation receives neither revenues nor metal from the area.

A mining operation would create employment where little now exists. This "new wealth" would create sources of tax revenues, possibly exceeding the amount "lost" by the increased depletion allowance.

Even if direct incentives are available for strategic materials, it is doubtful whether major exploration companies will go far afield in the search for them. The historic districts and known deposits will be the foci of attention, at least in the United States.

American corporations have the opportunity to make a choice between exploring at home, or in some foreign country, or ceasing exploration altogether. Not a few have chosen the latter course. Those who remain hedge, and do some of both.

Vertically integrated base metal producers would prefer captive, domestic mining operations to feed their existing metallurgical plants. However, in many cases, the ore grades of their older, domestic mining operations are too low, even in the high metal price periods, to provide the funds necessary for capital improvements and profit.

"Capital goes where it is loved" is an old saying - but the statement is not necessarily false because it is old.

For example, at the present time, many North American metal producers, and others, are considering very substantial copper mining investments in Chile. Their view - why search for hidden copper deposits in the U.S. and elsewhere, only to fight long and expensive land and environmental problems, exploration uncertainty, and hazy government mineral policy here?

In Chile, there are numerous IDENTIFIED copper deposits, known copper content is as much as 50 percent higher than in the U.S., and the government, even if not a model democracy, at least appears to have a firm and definite minerals policy.

One of those interviewed noted that "the Sierra Club and its preservationist, know-nothing followers, doesn't have any influence in Santiago, thank God!"

Some foreign countries, like Australia, Turkey, Brazil, etc., also offer semi-virgin ground for exploration. Many domestic explorers are tired of turning over the same old shopworn American prospects.

Whether a company decides to explore at home or abroad, exploration is still an expensive and risky business. At a recent American Mining Congress meeting, a paper given by D. Cook of Freeport Minerals, entitled: "Exploration or Acquisition - The Options for Acquiring Viable Metallic Mineral Deposits" included some interesting exploration statistics. Sixty-nine "world-class" deposits have been found in the past 30 years, or 2.3 per year. (See lists in Appendix F). Of the 69, 22 were in the U.S., 14 in Canada, 11 in Latin America, and the others scattered about the countries of the free world. None of these deposits were of strategic materials under study in this report. At 1982 exploration expenditures by 15 major international mining companies and 9 oil companies, the cost of locating or acquiring a "world class" deposit was $290.0 million. The figure would be considerably higher if monies expended for exploration by small and medium sized corporations were included.

Strategic Materials

Among those interviewed, there was a strong consensus that the United States does not contain really significant unknown, ECONOMIC (now, and in the reasonably foreseeable future) deposits of chromite, cobalt and platinum group metals.

Geologists are a contentious lot, and there are some who will disagree with this collective majority opinion. These may hold that increased geologic knowledge, better technology, and fresh exploration concepts can find new, economic deposits of the strategic materials under consideration. Such a scenario is, admittedly, possible. However, we, and most of those interviewed, are judging by PROBABILITIES, not POSSIBILITIES. All things are possible, but not necessarily probable.

In the context employed above, the word "significant" refers to a deposit which could produce about 10 percent of the domestic consumption of any one of the strategic metals.

Even if such deposits do exist, the apparent risk/reward ratio and the identified South African reserves preclude much action being taken on the status quo basis.

There was not as strong a consensus on manganese. A few men thought that economic deposits of manganese might be present in the U.S. Two pointed out that known concentrations of manganese, e.g. Artillery Peak, Arizona, could, with relatively modest metallurgical and economic improvements, be "made into ore bodies" in the near future.

However, again it should be noted that the domestic manganese market is not large enough to attract major, long-term explorers, developers and producers. A few large companies, some government owned, dominate the world market, and there is a trend to forward intergration by ore producers into ferro-manganese production. This indicates that any domestic ore discovery would have to be important enough to support, not only the mine, but also a substantial investment in a metallurgical plant.

One thing was very definite. No one interviewed thought that he could sell a geologically well conceived strategic metals exploration program to his management now, or in the near future.

Technological Developments and Scenarios

This scenario assumes that mineral exploration science and technology advances at an "optimum rate" to the early 1990's; that there are no substantial contraints in R&D funding, manpower and the status of the minerals industry.

In general, no one, including the authors, expects a "breakthrough" in mineral exploration technology within the next ten years.

Most current tools and techniques will become more precise and refined, due to the gradual accretion of new mineral exploration and general scientific knowledge.

Mineral exploration groups will be organized, managed and staffed much as they are today. The level of funding will at least match, in real terms, today's expenditure in the domestic industry of approximately $350,000 per professional employee per year.

It is reported (Barber, G.A., personal communication, 1983) that a recent private survey concluded that MAJOR exploration groups, on a WORLD WIDE basis, average approximately $250,000 per professional per year.

These differing figures may result from their bases of calculation. However, they may indicate just how much more costly domestic exploration is than that in foreign countries.

We could obtain no meaningful opinions on potential developments in mineral exploration technology which may occur early in the next century. Statements included: "Who knows?"; "Not much."; "No one can say."; "Just like today, maybe slightly better."; "Unless geologists and their management are much better, the second hundred meters will be very tough."

Geologists can be voluble, opinionated, far out thinkers, and this lack of definite comment was somewhat surprising. We speculate that this thought pattern may be due to the geologists' historic viewpoint of mineral exploration. There is little technology in the exploration armory of today which a competent geologist of 30 years ago would not comprehend, or grasp, with a brief study. This cannot be said of many other scientific fields. Since the mineral explorationist has never seen a "quantum jump" in his technology (not theory), perhaps one cannot be visualized.

Until quite recently, the mineral exploration geologist was wholly a creature of his employer, the mining industry. The industry is, quite possibly, the least innovative of any major industrial group. The industry's "thought processes" are not conducive to "freedom of imagination".

Genetic Theory

The better concepts in this field will be more fully utilized by practical explorationists. "Better", in this case, means the most immediately successful.

There will be somewhat increased interaction between industry and academia; and the plate tectonic-ore genesis conceptual revolution will keep slowly evolving.

Advances in this field are expected to call attention to some hitherto ignored, or currently unknown, geologic environments for some metals, particularly gold, silver, and perhaps, some base and strategic metals.

No one interviewed, however, felt that any ten year development of genetic theory or modelling will allow explorationists to accurately fix the location and approximate quality of any type of mineral deposit. In fact, there was strong doubt that such a thing could ever be done.

For most strategic metals, there is a relatively small and old knowledge "base" to build from, so familiarity with, and interest in, their special geologic environments will probably continue to lag behind that of most other metals.

Technology

Geosat imagery and other associated data will be cautiously employed, especially when some of the uncertainties of spectral interpretation are removed, as seems likely if additional R&D funding is supplied.

However, many large, broadly geologically favorable areas of the earth's crust have post-ore cover of varying types. No satellite related technical development will provide penetration of this cover.

Geophysical techniques are expected to improve only slightly, since many methods are approaching absolute barriers imposed by physical laws.

Miniaturization of geophysical instrumentation will be much more highly developed. The subsequent increased employment of down-the-hole geophysics will give, in effect, greater depth penetration in areas being explored. However, this improvement will be of little use in the initial or reconnaissance stages of exploration.

Data interpretation is expected to improve somewhat, but it is still expected to be a substantial problem, particularly where "background noise" is prevalent.

The main advances in geochemical exploration are expected to occur in instrumentation and in analytical techniques. Hand-held and drill hole adaptive, direct in-situ analytical devices will be available for some elements. These will probably not include the strategic metals, except perhaps, the platinum group metals, since there is little economic interest in the others.

Semi-automated wet chemical analytical methods will be standard, and reproducibility and sensitivity increased. However, more highly trained, and more costly, technicians and analysts will be required for this work.

Helicopter-borne spectral reflectance instrumentation may be used to geochemically screen vegetation in large forested areas. This instrumentation may be a "spinoff" from satellite research. In addition, some practical instrumentation should be available to make direct measurements of gases evolved by the decomposition of some economic minerals in the near surface environment.

Accurate, original sampling will still be a basic problem, since the labor intensive collection techniques will still have to rely on subjective, on-the-spot judgement factors.

Drilling techniques in the early 1990's are not expected to be much different from those employed now. Most explorers glumly look forward to increased drilling costs and approximately the same drilling efficiency as we have today.

If the approximate rate of growth in the average drilling depth continues, with its attendant increased cost per hole, it is probable that fewer holes will be drilled on any one target. This perceived problem bothers everyone, but ideas and answers are in extremely short supply.

In summary, it is concluded that the exploration scene of the early 1990's will not be greatly different from that of today, except, as most experts think, it will be more expensive.

A second scenario, one of overall, rather than technical feasibility, is not realistic under the given conditions. One of the principal constraints on the overall scenario is land availability.

The availability of mineral lands suitable for exploration will become an increasingly serious and very limiting factor for mineral exploration in the United States.

In a recent news release (Wall Street Journal, 9/8/83, page 4), the Census Bureau is quoted as estimating that 60 percent of Americans will be living in the south or west in the year 2000. This represents about 42.0 million additional people than at present.

The arithmetic average of the estimated percentage increase of population for the twelve westernmost states (excluding Hawaii) is 67.3 percent. These states undoubtedly possess the highest overall mineral potential. Large areas of these states are not now available for exploration because of past, and continuing government action.

Each percent increase in the western population will stimulate an unknown but certainly increased demand for more additional lands for housing, its related infrastructure, recreation areas, parks, vacation sites, etc. - and, for additional raw materials.

This competitive conflict for land and water cannot be settled by science and technology. Political decisions, most currently unpalatable, will be required.

The explorer and miner finds himself in a situation analogous to those who advocate chemical waste disposal sites, new prisons, etc. Everyone agrees that these items, like mines, are useful, important and necessary - but they must be located somewhere else, other than in "our special area".

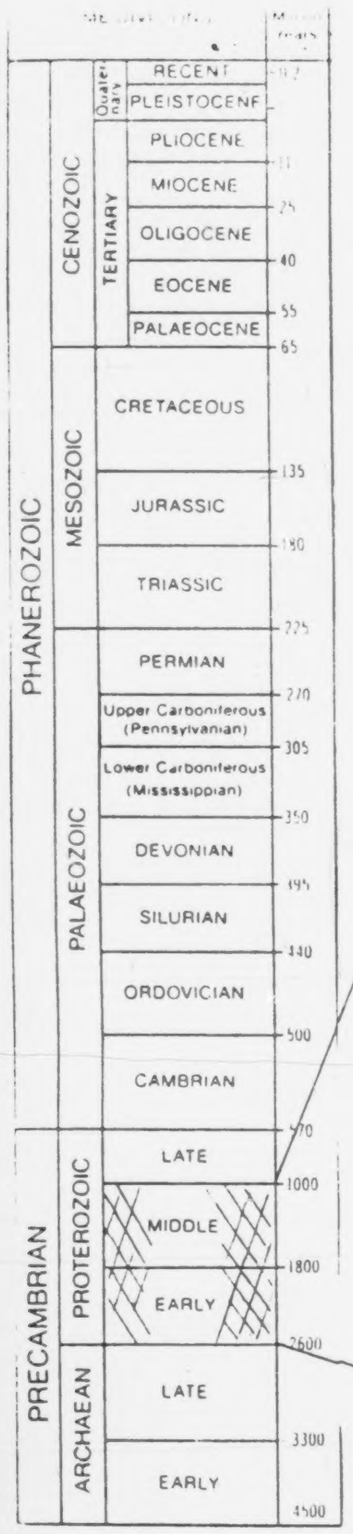
Technology and Methodology

No new theory or advanced technology will locate or produce minerals from lands where the minerals sought do not exist, or from lands which are not available for exploration-exploitation.

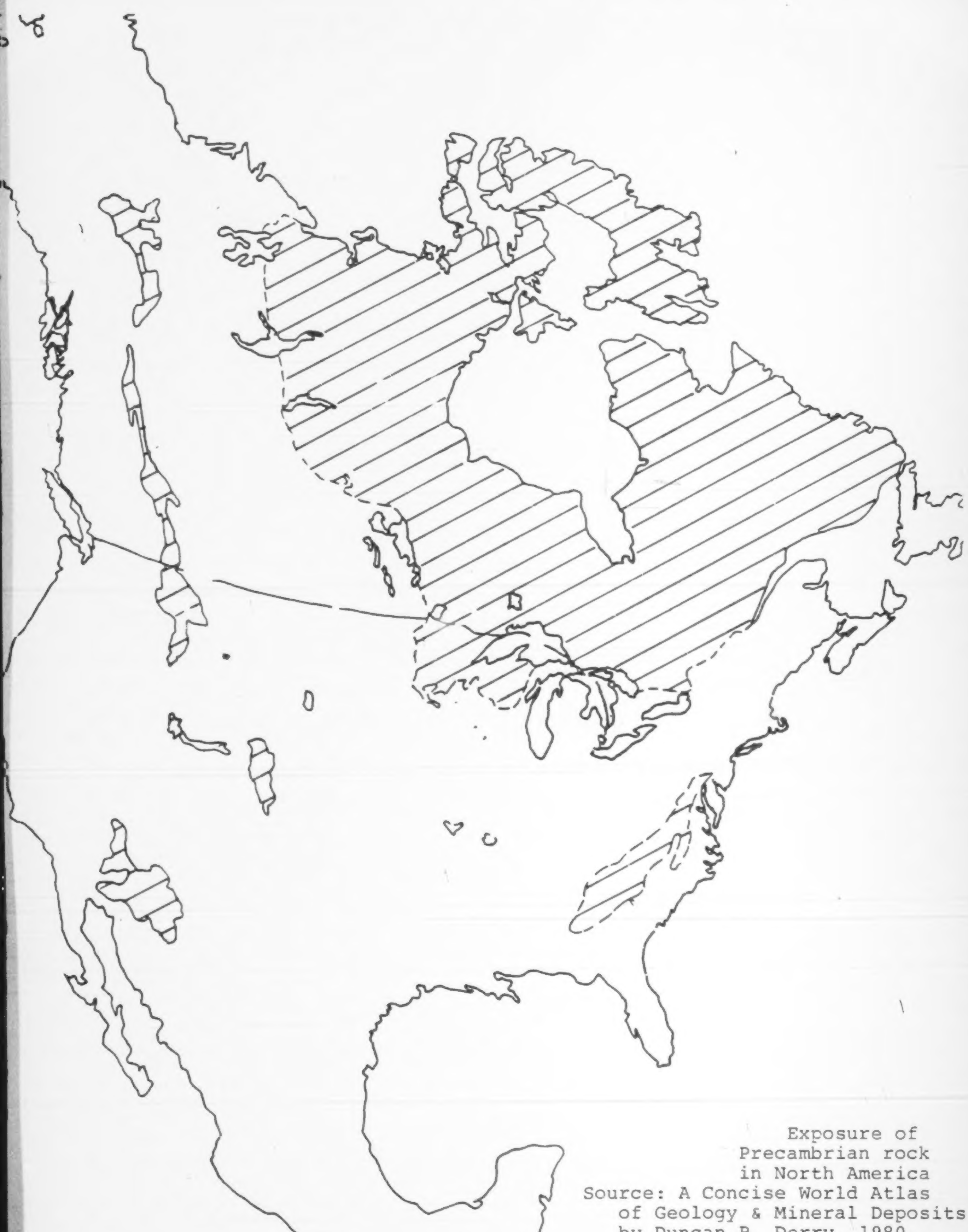
At present, known world resources of strategic materials are adequate to the year 2000 and beyond. However, should there be an interruption in supply from South African or USSR sources, the United States would have to rely on imports from other countries; stockpiles; and/or the development of currently known, but subeconomic domestic resources. The development of domestic resources is technically feasible if economic necessity dictates. Exploration for additional domestic deposits will proceed only insofar as there are perceived economic benefits to the explorer, geologically favorable areas, and land is available for mining.

In North America, the most geologically favorable areas for location of important deposits of chromite and nickel-copper-cobalt sulfides with associated platinum group metals, are restricted to mafic/ultramafic intrusives within the Precambrian rocks. The time chart on page 17a shows the time bound nature of the world's major economic deposits of some strategic materials. The figure on page 17b shows the exposure of Precambrian rocks in North America. In the United States, the Precambrian exposure is roughly limited to Michigan, Minnesota and Wis-

Time chart of a few of world's major economic deposits of strategic materials


PHANEROZOIC
CENOZOIC
Quaternary
RECENT
PLEISTOCENE
TERTIARY
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALAEOCENE
MESOZOIC
CRETACEOUS
JURASSIC
TRIASSIC
PALAEOZOIC
PERMIAN
Upper Carboniferous (Pennsylvanian)
Lower Carboniferous (Mississippian)
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
PRECAMBRIAN
PROTEROZOIC
LATE
MIDDLE
EARLY
ARCHAEAN
LATE
EARLY
11
25
40
55
65
135
180
225
270
305
350
395
440
500
570
1000
1800
2600
3300
4500

Deposit	Location	Approx.Age (million yrs.)	Commodity
Katanga	Zambia-Zaire	1000-1800	Cobalt
Duluth Gabbro	Minnesota	1000-1500	Nickel-Cobalt
Sudbury	Ontario	2000-2100	Nickel-Copper-Platinum
Bushveld	S. Africa	2000-2100	Chromite-Platinum
Outokumpu	Finland	1800-2300	Copper-Nickel-Cobalt
Kemi	Finland	2400-2500	Chromite
Stillwater	Montana	2600-2700	Chromite-Platinum
Great Dyke	Zimbabwe	2400-2500	Chromite-Platinum



Exposure of
Precambrian rock
in North America
Source: A Concise World Atlas
of Geology & Mineral Deposits
by Duncan R. Derry, 1980

consin, plus smaller, scattered areas in other states, notably Montana, Idaho, Colorado, and Arizona. This basic fact cannot be ignored when the nation's strategic material assessment is being considered.

It is conceivable that presently unidentified geologic environments in the U.S. may contain these metals. However, exploration for, and in, such environments amplifies the already high risk of exploration. The chance of success in any particular venture is a function of the probability of success of each stage of the exploration process. The risk factors must be multiplied by each other. Another high risk factor will lower the calculated expectation of success.

Manganese deposits are not as exclusively time bound as the other metals. Current and future applications of genetic theory, model analogy and technology may possibly locate deposits of manganese in North America. However, there is presently little, or no, exploration interest in domestic manganese exploration.

Until long-term, preferably free market, economic incentives are available, there will be no significant exploration for, or development of, known resources of strategic materials in the United States.

The terms "free market" and "incentives" could be considered contradictory by some. However, "free market incentive" simply means profit. Profit commensurate to the risk involved. For strategic metals, this would require: higher than average grades and/or lower than average cost ores; substantial and dependable markets; and some assurance of long-term stability in the domestic economy.

The scenarios, if based solely on advances in total exploration technology, are not realistic.

Exploration methodology must not and cannot be viewed separately from technical advances in extractive metallurgy, mining techniques, etc.

For the long term, advances in other fields of science and engineering, will enable mankind to produce his material needs from today's known resources.

It is possible to conceive of genetically modified forms of plant or animal life being "invented", which could selectively liberate and concentrate the small amounts of metals present in tailings, waste dumps and other presently subeconomic mineral resources. Coupled with in-situ mining, improved chemical extraction techniques, and other similar advances, it is thought that "biotechnology" will become a major factor in fulfilling mankind's long-term raw material demands.

One specific example: Although silver is toxic to a wide range of bacteria, it has been observed that certain species accumulate silver within their cells. The bacteria's metabolism will liberate silver from sulfide minerals. In some experiments, the residual bacterial mass contains as much as 25% silver. "This finding has interesting practical applications for the recovery of silver...". (Pooley, F.E., Nature, Vol. 296, 4/15/82).

A few forethinking organizations, such as the Rothschild Bank and Rio Tinto Zinc, are financing research in this field at the present time.

Most of mankind's long-range raw material supplies may be delivered by the biochemists, not the geologists.

Glossary

Basalt: Lava that is relatively mafic (having less than 55% silica) and being dark in color.

Basin: The topographical use of the word indicates a depressed area into which the adjacent land drains. In structural geology it indicates a syncline that is circular or elliptical in plan with the beds dipping inward.

Craton: A major structural unit of the Earth's Crust, relatively immobile and generally consisting of ancient igneous and/or metamorphic rocks. The word is almost synonvmous with "shield".

Crust: As used in the composition of the Earth it is the outer layer overlying the mantle and varying from continental crust (average about 35 km thick) to oceanic crust (about 9 km thick).

Dyke: A tabular body of igneous rock cutting across the structure of adjacent rocks.

Fault: A fracture or fracture zone along which there has been displacement of the sides relative to one another, parallel to the fracture.

Felsic: Describes an igneous rock composed of light colored minerals and containing over 55% silica.

Geosynclines: Major structural and sedimentational units of the crust of the Earth. They consist of elongated basins which become filled with great thicknesses of sediments and often volcanic units. Progressive subsidence of the basin floor occurs under the weight of the accumulated pile of sediments and subsequent deformation results in a fold-mountain chain.

Granite: A plutonic rock consisting essentially of alkali feldspar and quartz, minor quantities of mica and sometimes hornblende.

Horizon: A time-plane in a sedimentary or volcanic series recognizable by some characteristic feature such as specific fossils or lithology.

Igneous: A rock or mineral formed by crystallization from molten or partially molten material. Contrasted with sedimentary rocks.

Intrusive: An igneous rock unit having, while in the molten state, penetrated into, or between, other rocks but solidified before reaching the surface,

Laterite: Residual iron-rich surface deposit resulting from alternating wet and dry seasons in tropical or subtropical latitudes.

Lithology: Describes the physical characteristic of a rock - color, composition, grain size.

Mafic: Describes igneous rock composed predominantly of magnesian silicates but containing under 55% silica. Dark in color.

Magma: Naturally-occurring mobile rock material generated within the Earth and capable of intrusion (e.g. granites) and extrusion (lavas).

Metamorphism: Metamorphic: Process by which consolidated rocks are altered in composition, texture or internal structure by heat, pressure and the introduction of new chemical substances.

Mid-Ocean Ridge: A continuous narrow (about 1,500 km) median mountain range extending through the North and South Atlantic Oceans, the Indian Ocean and the South Pacific Ocean. It has a central rift valley up which lava erupts and about which sea floor spreading is believed to take place.

Orogeny: A period of mountain building particularly by folding but usually also involving faulting, intrusion and metamorphism.

Pangaea: The name proposed by Alfred Wegener for the "supercontinent" comprising all land masses on Earth.

Plate: One of the large segments of the Earth's crust varying in thickness from 50 to 250 km and including a portion of the upper mantle (lithosphere).

Plate Tectonics: The movement of plates relative to those adjoining.

Porphyry: Originally used to describe an intrusive rock containing relatively large crystals set in a finer-grained ground mass. May be applied to lavas having this characteristic.

Porphyry Copper: Disseminated copper minerals in a large body of porphyry but in a commercial sense may be applied to disseminated copper ore on a large scale in any felsic intrusive.

Remobilized: Remobilization: The process by which a mineral deposit is dissolved, transported in solution and redeposited in another place, sometimes resulting in an increased grade of ore.

Shield: A continental block of the Earth's crust (usually of Precambrian age) that has been relatively stable over a long period of time in contrast to the strong folding of bordering, geosynclinal belts.

Stratiform: Composed of layers.

Subduction: Descent of one tectonic unit under another.

Subduction Zone: A region along which one crustal plate descends relative to another, e.g. the descent of the Pacific Plate beneath the Andean Plate.

Sulfide Zone: That part of an orebody or vein not yet oxidized by air or surface water, and containing sulfide minerals.

Tectonic: An adjective used to relate a particular phenomenon to a structural or mountain-building concept. Plate Tectonics - a theory of global-scale dynamics involving the movement of many rigid plates of the Earth's crust.

Appendix A

Plate Tectonic Classification of Ore Deposits

by J.M. Guilbert, 1981

in

RELATIONS OF TECTONICS TO ORE DEPOSITS
IN THE SOUTHERN CORDILLERA

Arizona Geological Society Digest
Volume XIV

Appendix A: Plate Tectonic Classification of Ore Deposits

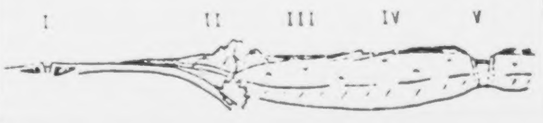


FIG 1. Schematic representation of the tectonic relationships of the five major plate tectonic ore deposit classification categories, including ore deposits associated with I Oceanic crust, II subducting, consuming continental margins, III back arc basins, IV cratonic shields, and V rift-related openings. The diagram shows a mid-oceanic ridge at left yielding through a trench-subduction zone to the continent itself. Highly generalized; not to scale. See accompanying Table 1.

TABLE I*

A Plate Tectonic Classification of Ore Deposits

I. Ore Deposits associated with Oceanic Crust
II. Ore Deposits associated with Subducting Margins
III. Ore Deposits associated with Back-arc Basins
IV. Ore Deposits associated with Cratons
V. Ore Deposits associated with Cratonic Openings

I. Ore deposits associated with mid-oceanic ridges and ocean floor/oceanic crust formation

- A. Plutonic - Oceanic Crust Layer 3
  - 1. Layered Mafic Intrusions
    - a. Latent alpine peridotite
      Chromite, Platinoids
      Alaska, Turkey, Cuba
    - b. Latent ophiolites
      Asbestos
      Quebec, USSR
- B. Volcanic - Oceanic Crust Layers 1 and 2 - Hydrothermal-Proximal
  - 1. Cyprus-type massive sulfides
  - 2. 'Black Smokers'
- C. Volcanic - Oceanic Crust Layer 1- Hydrothermal-Distal
  - 1. Mn-Cu-Ni-Co nodules
  - 2. Au-Fe association
  - 3. Fe-Mn oozes
- D. Sea Breach - Oceanic Crust Layers 1 and 2 with Supergene Activity
  - 1. Nickel Laterites
    New Caledonia

II. Ore deposits associated with consuming, subducting margins

- A. Obduction
  - 1. Alpine Peridotites - LMI - See IA
    - a. Chromite, Platinoids
      Alaska, Turkey, Cuba, Philippines
    - b. Asbestos
      Quebec, USSR, B.C.

---

[*] Ore deposits and districts in the United States and Canada are generally located by state or province, others by country. Deposits in the table are listed as examples only; the lists are by no means intended to be complete catalogs.

Table 1 (continued)

- c. Vermiculite
  - Montana, North Carolina
- 2. Alpine Peridotite with laterization
  - a. Nickel
    - Riddle, Oregon
- 3. Franciscan melange
  - a. Hg-Serp-Au
    - New Almaden, McLaughlin (?), California
- 4. Ophiolites - Massive Sulfides - See IB
  - a. Cu-Zn, Cyprus-type
    - Cyprus, Newfoundland, Italy, Timor

B. Ocean/Ocean - Island Arcs - 'Eugeoclines'

- 1. Proximal Massive Sulfides
  - a. Cu-Zn-Ag
    - Abitibi Belt, Ontario-Quebec; Noranda, Kidd Creek;
    - Yavapai Belt, Arizona; United Verde, Bruce;
    - Ducktown, Tennessee; Kuroko, Japan
  - b. Cu - Ni
    - Abitibi Belt - Alexo, Langmuir;
    - Yilgarn, Australia; Kambalda, Lutton;
    - Zimbabwe - Shangani, Damba
  - c. Pb - Zn
    - Sullivan, B.C., Rammelsberg, West Germany
- 2. Proximal Oxides
  - a. Iron Formation, Algoma Type
    - Abitibi Belt - Sherman, Adams
    - Yilgarn, Australia; Barberton Mt Land, RSA
- 3. Distal Oxides and Sulfides
  - a. Au
    - Abitibi - Larder Lake, Kirkland Lake, Ontario; Val d'Or, Quebec
    - Zimbabwe; Mayer District, Yavapai Belt
  - b. BIF + Au
    - Homestake, South Dakota; Morro Velho, Brazil;
    - Kolar, India; Contwoyto Lake, NWT
  - c. Iron Formation, Superior-Type
    - Biwabik of Minnesota, Wisconsin, Ontario
  - d. Pb-Zn
    - Iron King, Arizona
- 4. Porphyry copper-moly-gold
  - a. copper-moly
    - Atlas, Philippines
  - b. copper-gold
    - Panguna, Ok Tedi, Fiji (?)
- 5. Plutonic-Ultramafic
  - a. Asbestos,
    - Msauli, RSA; Swaziland

C. Ocean/Continent, Trench/Arc, Cordilleran Orogenics

- 1. Magmatic iron (Magnetite I-type, Steep Dip)
  - a. Plutonic magnetite
    - Nelson, Virginia; Pea Ridge, Missouri
  - b. Volcanic magnetite-hematite
    - Kiruna, Sweden; Cerro de Mercado, Mexico; El Lago, Chile
  - c. Igneous metamorphic-magnetite
    - Marcona, Peru; Chile; Grace-Cornwall, Pennsylvania; Santa Rita, New Mexico
- 2. Porphyry copper-moly (Magnetite I-type, Steep Dip)
  - a. Cu
    - San Manuel/Kalamazoo, Morenci, Arizona; Chuquicamata, Chile
  - b. Cu-Mo
    - Sierrita, Mineral Park, Arizona
  - c. Mo
    - Thompson Creek, Idaho; Brenda, Endako, B.C.; Quartz Hill, Alaska
  - d. Cu-Au
    - Bingham Canyon, Utah; Bajo La Alumbrera, Argentina

Table 1 (continued)

3. Igneous metamorphic
   a. Porphyry Copper contact
      Lakeshore, Christmas, Arizona; Santa Rita, N.M.; Carr Fork, Utah
   b. Hydrothermal Replacement
      Mission-Pima, Arizona; Linchburg, New Mexico
   c. Plutonic
      Darwin, California; Hanover-Fierro, N.M.
4. Cordilleran Vein - 'Mesothermal Metasomatic'
   a. Cu-Fe-As-S (Magnetite I-type, Steep Dip)
      Butte, Montana; Magma, Arizona; Morococha, Casapalca, Peru
   b. Pb-Zn-Ag (I-S-type, Shallow dip)
      Leadville, Gilman, Colorado Mineral Belt, Colorado;
      Goldfield, Nevada; Mayflower-Tintic-Ontario-Park City, Utah;
      Freiberg, East Germany
   c. Au
      Mother Lode-Grass Valley, California (?)
5. Porphyry Tin-Tungsten (Ilmenite, I-Type, Shallow Dip)
   a. Sn-W porphyries
      Potosi, Llallagua, Bolivia;
      Mount Pleasant, New Brunswick
   b. Sn rhyolites
      Mexico; New Mexico
6. Tin-Tungsten Granites (Ilmenite, S-Type, Shallow Dip [?])
   a. Tin granites
      Malaysia, Tasmania, Cornwall, Panasquiera
   b. Tungsten granites - with uranium?
      SW US - Las Guijas, Arizona; Darwin, California
7. Metamorphic Core Complexes (S-Type Granites)
   a. Tungsten, Uranium (?)
      Shushwap Complex, Washington; southwestern Arizona (?)
8. Complex Zoned Granitic PegmatitesBlack Hills, S.D.; White Picacho, Az.; Maine-New
   Hampshire-Conn.-North Carolina
9. Rare Earth Pegmatites
   Ravalli, Montana; Barringer Hills, Texas; Minas Gerais, Brazil
10. Granitic Uranium
   a. Pegmatitic
      McInstry, North Carolina; Maine-New Hampshire
   b. Migmatitic
      Rossing, Namibia; Jabiluka, Australia (?)
11. Industrial rocks
   a. Granites
      New England, Georgia, California
   b. Syenites
      Egypt, Quebec, Arkansas
7. Lacustrine evaporites
   a. High level tectonic basins
      Piceance-Gosiute, Colorado-Wyoming-Utah
   b. Chain Lakes
      Owens Lake-Searles Lake-Death Valley, California

D. Ocean/Continent: Extension
1. Porphyry copper - soda alkalic affinity
   Stikine, Afton, Caribou-Bell, B.C.
2. Stockwork-moly (I-type, Steepening Slab (?), Rifting)
   Climax, Henderson, Mt. Emmons, Colorado
   Questa, New Mexico; Cave Creek, Texas
3. Epithermal-Ignimbrite association
   a. Silver rich
      Comstock, Nevada; Pachuca, Guanajuato, Mexico

Table 1 (continued)

- a. Mercury-Uranium
  - McDermitt, Oregon
- b. Silver
  - Creede, Summitville, Colorado
- 5. 'Low Grade Silver' - Caldera-Lake sediments
  - Candelaria, California

III. Ore deposits associated with ensialic-ensimatic back-arc basins

- A. Volcanic tendencies - outboard (arc) side
  - 1. Pb-Zn-Cu
    - Broken Hill, NSW, Australia; Black Mt.-Aggeneys-Gamsberg, RSA; North Coldstream, Ireland; New Brunswick-Maine-Caledonides
  - 2. Pb-Zn
    - Mt Isa, NSW; Sullivan, B.C. (?)
  - 3. Sn
    - Tasmania
- B. Sedimentary tendencies-inboard (continent) side
  - 1. Pb-Zn-'Black Shale Hosted'
    - Howards Pass, NWT; McArthur River, NSW; Great Gossan Lead, Virginia; Tynagh, Ireland

IV. Ore deposits associated with Cratons

- A. Geosyncline-miogeocline-continental shelf
  - 1. Industrial rocks
    - a. Limestone
      - Bedford, Indiana
    - b. Sandstone
      - Berea, Kentucky; St. Peter, Illinois
    - c. Shale-slate
      - Argyll, Pennsylvania
  - 2. Iron ores
    - Clinton, Alabama; Minette, Alsace-Lorraine, France
- B. Littoral margins
  - 1. Base metal - Cu-Co-U
    - Copper Belt, Zambia; Kupferschiefer, East Germany-Poland
  - 2. Hydrocarbons - Petroleum
    - Arabia, Gulf Coast, Mexico
  - 3. Placers
    - a. Gold
      - Witwatersrand, RSA; Jacobina, Brazil
    - b. Uranium
      - Witwatersrand, RSA; Elliot Lake, Ontario
    - c. Diamonds
      - Namibia, Zaire
    - d. Titanium-Rare Earth Elements
      - Florida, Australia, India
  - 4. Phosphates
    - Florida, North Carolina; Morocco
- C. Epicontinental
  - 1. Adjacent to sedimentary basins
    - a. Mississippi Valley Deposits
      - Viburnum Trend, Missouri; Pine Point, NWT
    - b. Irish stratabound (?)
      - Tara, Ireland
  - 2. Unconformity-related
    - a. Uranium
      - Colorado Plateau, Wyoming roll-front; Athabasca Basin-Cluff Lake, Alberta; Jabiluka Australia (?)
    - b. Copper-Uranium
      - Olympic Dam, Australia

Table 1 (continued)

- 3. Residual or transported clays,soils,organics
  - a. Dirt - soil
  - b. Laterites - Ni, Al, Fe, Co
    - Guianas; Jamaica
  - c. Clays - fire, ball, and flint
    - Missouri, Kentucky, Pennsylvania
  - d. Kaolins
    - Georgia
  - e. Underclays
    - Pennsylvania, West Virginia
  - f. Coal
    - Pennsylvania, West Virginia, Montana, Europe, China
- 4. Placers
  - a. Gold-Chromite
    - Western United States
  - b. Gold-Chromite-Platinum
    - Alaska
  - c. Chromite-Platinum
    - Urals, USSR

V. Ore deposits associated with cratonic openings

- A. Pre-rift arching
  - 1. Kimberlites
    - a. Diamonds
      - Kimberley, Pretoria, RSA; Lesotho; Murfreesboro, Arkansas; Colorado; Australia
  - 2. Carbonatites
    - a. Rare Earth Element
      - Mountain Pass, California
    - b. Phosphate-Titanium-Copper
      - Palabora, RSA
    - c. Phosphate-Titanium-Niobium
      - Magnet Cove, Arkansas
  - 3. Alkalic Intrusives
    - a. Syenites
      - Monteregnian Province, Quebec; Little Rock, Arkansas
  - 4. Anorthosites
    - a. Titanomagnetite
      - Sanford Lake, New York; Lac Tio-Allard Lake, Quebec
  - 5. Layered Mafic Intrusions
    - a. Chromium-Platinum
      - Bushveld Igneous Complex, RSA; Great Dyke, Zimbabwe
    - b. Copper-Nickel
      - Sudbury, Ontario; Stillwater Complex, Montana; Duluth Complex, Minnesota
  - 6. Continental Basalts
    - a. Co-Ag-Ni-As
      - Cobalt, Ontario; Annaberg, West Germany
    - b. Asbestos
      - Salt River Canyon, Arizona
  - 7. Moly-Silica
    - a. Molybdenum
      - Gigantic, Zimbabwe
- B. Rifting
  - 1. Alkali volcanism and lakes
    - a. Trona-Dawsonite
      - East African Rifts
    - b. Carbonatites
      - Mbeya, Tundulu, Africa

Table 1 (continued)

C. Proto-oceanic gulf - Aulacogens
    1. Cu-Zn-Mn-Fe-Pb-Ba
        Red Sea brines
    2. Cu-Zn-Ag
        Salton Sea brines
    3. Cu-Mn-Ag
        Boleo-Lucifer, Baja California, Mexico
    4. Evaporites-K-Na-Mg-Cl
        Carlsbad, New Mexico; Ethiopia

D. Narrow shallow ocean
    See III - Ore deposits associated with back arc basins

E. Open ocean
    1. Mn-Cu-Co-Ni Marine Nodules See I-C
        East Pacific Basin

Appendix B

Example of an
Exploration Flow Chart
courtesy
Callahan Mining Corporation

Appendix B

CALLAHAN MINING CORP. EXPLORATION FLOW CHART

STAGE	GENERATIVE				EXPLORATION			PRE-DEVELOPMENT			DEVELOPMENT
PHASE	MODEL DEVELOPMENT & RESEARCH	RECONNAISSANCE PHASE I	RECONNAISSANCE PHASE II	PROPERTY EVALUATION	ORE DISCOVERY	ORE DEFINITION	ORE DELINEATION	ORE CONFIRMATION	ENGINEERING DESIGN	FEASIBILITY ENGINEERING	
ACTIVITIES	• Concept formulation • Data accumulation • Area selection • Understand regional geologic setting • Study geology of mineral occurrences	• District scale physical exploration • Target zone identification • If successful – leads to Reconnaissance, Phase II	• Detailed physical exploration • Target identification at property scale • If successful – leads to property evaluation	• If successful – Property acquisition request • Geochemistry • Detailed mapping • MAG, VLF	• Define & characterize mineralization, host rock & alteration • ± Drilling • ± Geochemistry • ± Geophysics	• Define dimensions, geometry and tenor of mineralization • Drill promising additional targets	• Ore delineation. • Drill ore zones or encouraging geologic, geochemical, geophysical trends. • Revise model.	• Close space drilling. • Acquire metallurgical, mining, environmental data sufficient for pre-engineering evaluation.	• Acquire general arrangement drawings, single line piping instrumentation diagrams, and material lists. • Refine metallurgy • Bulk sample and pilot plant if required. • Complete environmental impact assessment. • Establish mining method	• Complete 40% of final engineering.	
RESULT	RECON PROPOSAL REPORT	RECON REPORT	DRILL TARGET IDENTIFICATION	PROPERTY ACQUISITION	ESTABLISH EXPLORATION MODEL	EXPLORATION EVALUATION I (Accuracy ± 45%)	EXPLORATION EVALUATION II (Accuracy ± 35%)	PRE-ENGINEERING EVALUATION (Accuracy ± 25%)	ENGINEERING & DESIGN REPORT (Accuracy ± 15%)	FINAL FEASIBILITY REPORT (Accuracy ± 10%)	

Appendix C

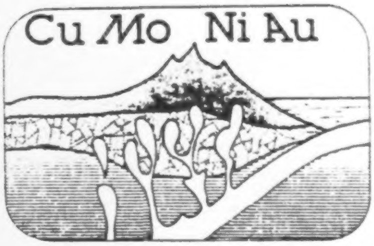
Methods of Predictive Metallogeny

from

Geoscience Canada, Volume 10, Number 2

Appendix C

Methods of Predictive Metallogeny: A Symposium



Introduction

A. Sutherland Brown
B.C. Ministry of Energy, Mines &
Petroleum Resources
Geological Branch,
Mineral Resources Division
Parliament Buildings
Victoria, B.C. V8V 1X4

G.B. Leech
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

The Committee of Provincial Geologists perceived the need for more open discussion of methods of predictive metallogeny and, accordingly, asked the Mineral Deposit Division of GAC whether it would cosponsor a panel discussion on the subject. As a result, we (Sutherland Brown and Leech) became co-chairmen, invited the panel members and organized the session at the Joint Annual Meeting at Winnipeg 1982. Various provincial surveys provided funds to facilitate travel for Russian and American speakers. The written papers were reviewed by the co-chairmen, and G.B. Leech prepared an edited condensation of the discussion from tapes prepared under the auspices of Winnipeg '82.

Predictive metallogeny has two principal but diverse applications:

1. exploration planning and target identification (industry)
2. resource appraisals and the protection of mineral lands (government)

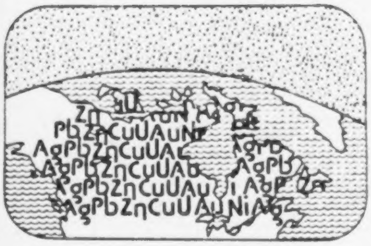
The discovery of deeply buried mineral deposits that we will need in the future will require better predictive metallogeny to augment what will clearly be remote signals from geophysics and geochemistry before deep drilling can be undertaken with any confidence. Governments need regional and local resource appraisals for economic planning and land use decisions. The end product of predictive studies will differ for these two users. The papers and discussion presented here clearly reveal these two aspects.

The chairmen wished to have speakers representing a diversity of approaches and wished to stimulate discussion. We invited four speakers:

Dr. D.F. Sangster, to give a historical review of the Canadian experience
Dr. D.V. Rundquist, to discuss Soviet methods
Dr. DeVerle Harris, to give a quantitative approach
Dr. George Mannard, to give an industry point of view

In order to stimulate discussion, we asked J.D. Boldy and R.J. Cathro to come prepared to comment on the papers from the point of view of Precambrian Shield and Cordilleran experience. Much valuable discussion between audience and speakers ensued. Unfortunately, Dr. Rundquist's authorized paper is not illustrated with the specific examples he discussed.

George Mannard died suddenly, three months after the Symposium. The chairmen and sponsors wish to acknowledge his ready acceptance of his role in this symposium, which was typical of his life of dedication to geoscience and to the study of mineral deposits.



1. The Canadian Experience in Mineral Resource Assessment

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Summary

The first Canada-wide, non-industry resource assessment was A.H. Lang's uranium metallogenic map, published in 1958. Since then approximately two dozen resource assessments of either the entire country or various parts of it have been produced by the federal and certain provincial geological surveys. Most research in resource assessment methods, however, has been carried out in the Geological Survey of Canada; some has been done within provincial geological surveys, but little or none has emerged from Canadian universities.

Methods used in Canada during the 24-year span have ranged from statistically dominant and geologically subordinate to the reverse, and the resulting assessments have ranged from quantitative to qualitative. Of the various methods that have been proposed, developed and tested by far the most widely used is that employing conceptual models of separate and distinct types of deposits. The models are erected by mineral deposits geologists on the basis of experience, research and examination of many examples of each deposit-type. Essential and integral parts of each conceptual model are its regional geological parameters, and it is these parameters which are sought in resource evaluation studies using the conceptual model method. This method, as presently used in Canada, usually results in an arbitrary rating of selected areas in terms of their assessed potential to contain undiscovered deposits.

Numerous examples of resource assessment using the conceptual model method recently have been published by both federal and provincial governments. These resource assessments are presented in such a manner that they can be used for government land use decisions as well as for initial phases of mineral exploration.

Introduction

Mineral resource assessment in Canada probably had its origins in the first years of geological study of the nation. Sir William Logan recognized the similarity in geology between Carboniferous rocks in Nova Scotia and those of the United Kingdom, and predicted that the former would therefore be favourable for the occurrence of coal. In the intervening years, most geological reports of specific areas, whether published by federal or provincial agencies, contain some comment on the perceived favourability of the area in question to contain undiscoverd mineral deposits.

On a national scale, however, the first mineral resource assessment was probably that of A.H. Lang of the Geological Survey of Canada. In 1958, Lang published a map of Canada outlining those areas of the country he felt were particularly favourable for the occurrence of undiscovered uranium deposits. In the 24 years following Lang's assessment, several methods of resource assessment have been tried by many different Canadian workers and agencies. The present paper will describe briefly selected examples of these early Canadian methods and will conclude with a description of a method in common use by the Geological Survey of Canada. As used in this report, "mineral resource assessment (or evaluation)" refers to the prognostication of undiscovered deposits; it does not refer to the geological or economic evaluation of known deposits.

Historical Review

Selected examples of various Canadian resource assessment studies carried out since Lang's initial 1958 map are listed in Table I and reveal that publications on the subject in Canada here averaged better than one a year for the past two decades. The table also shows that initial attempts to produce quantitative estimates have, in recent years, given way to increased emphasis on qualitative methods of analysis, probably reflecting a somewhat more sober and realistic approach to an extremely complex subject.

Roscoe (1966) reported on the U-Th potential of the country in terms of a map of Canada. Different map patterns outlined areas considered favourable for pegmatite, pitchblende and conglomerate deposits.

In 1970, Barry and Freyman published their assessment of the mineral endowment of the Canadian northwest and expressed their results as contoured values of tons-of-metal per square mile. The authors used a modified Delphi method to collect, on standard printed forms, the opinion of several experts supposedly knowledgeable of the geology and mineral deposits of this part of Canada.

The year 1972 saw two very different approaches to mineral resource assessment evolve within the Geological Survey of Canada. One method, developed by Agterberg and his coworkers, was geostatistical in nature and involved multi-variate analyses of individual cells of a grid superimposed on the area in question, in this case the Abitibi Belt of the Canadian Shield (Agterberg *et al.*, 1972). The product was expressed as contours of metal probability. Concurrently with Agterberg's activities, another group in the Geological Survey was developing a totally geological method of resource assessment based on the conceptual model technique. By this method, the geology of the area being assessed is compared with the diagnostic geological parameters of separate deposit-types (e.g., porphyry copper, skarn tungsten, stratiform lead-zinc, etc.). The diagnostic parameters used are those deduced by G.S.C. mineral deposits geologists as a result of direct observation of many deposits in Canada and throughout the world, and by extensive literature survey. The actual assessment is performed by a small group of individual geologists, usually 1-3 per deposit type. Carried out in this manner, the method is similar to that described as the *simple subjective* method (Singer and Mosier, 1981). Examples of this method will be described in somewhat more detail later but, in 1972, the geologically-based conceptual model method produced an estimate of Canada's undiscovered resources of Cu, Ni, Pb, Zn, Mo, U and Fe. The results of this project, known as "Operation September", constituted an unpublished internal report of the Department of Energy, Mines and Resources. Operation September, *ad hoc* though it was, firmly established the conceptual model methodology used in all subsequent official resource assessment studies performed by the Geological Survey of Canada.

At the same time as resource assessment methods were evolving within the G.S.C., workers in a sister branch, now known as the Mineral Policy Sector, concluded a study in cooperation with the Manitoba Mines Branch, on the undiscovered endowment of a dozen or so commodities in the Canadian Shield of northern Manitoba. A modified Delphi method (Harris *et al.*, 1970) was used and results were expressed as units of metal weight per cell of 400 square miles (Azis *et al.*, 1972).

In the mid-1970s, two new players entered the mineral resource assessment game. Ontario (Robertson, 1975) began publication of a series of mineral potential maps in which geologically-defined areas were assigned a seven-fold rating for a variety of metallic and non-metallic commodities. The method used was geologically-based and very similar to that employed by the G.S.C. During this time also, the British Columbia Department of Mines began publishing a series of maps (McCartney *et al.*, 1974; McCartney and Matheson, 1974) depicting the geological probability of certain commodities to occur in selected, geologically-defined areas.

By 1980, a joint project of the Manitoba Department of Energy and Mines and the Geological Survey of Canada had produced a geological evaluation of the Precambrian massive sulphide potential of northern Manitoba (Gale *et al.*, 1980). Simple subjective probability was used to express potential in terms of a six-fold rating scheme. The project differed, however, from all other resource assessments in that it did not report evaluations of specific commodities (e.g., Cu, Zn, Ni) but, rather, of a deposit-type (i.e., volcanogenic massive sulphides). In one sense, therefore, this study served to re-emphasize that although most if not all assessments are reported in terms of commodities, the actual assessment is carried out in terms of geological deposit-types. Conversion of deposit-type potential into commodity potential involves several assumptions and introduces a number of errors which the Manitoba-G.S.C. study attempted to avoid.

Iron and Uranium: Special Cases

A glance at Table I reveals a long history of uranium and iron resource assessments. For this reason, and because treatment of these commodities has been somewhat different than for other metals, uranium and iron are singled out for special consideration.

Iron. Although most early surveys of Canadian iron resources were largely inventory in nature, they did contain modest prognostications of undiscovered iron deposits (e.g., Tanton, 1952, p. 340; Gross, 1970b; Table I). The iron deposits were first subdivided into distinct deposit-types and, for each, conceptual descriptive and genetic models were established (Gross, 1965; 1970a). By 1967, Canadian reserves and prognosticated resources had been calculated according to the different deposit-types, although the results were not published until several years later (Gross, 1970b; Tables 1 and 4). In spite of these prognostications, however, it is nevertheless true that the main emphasis in iron appraisals is the assessment or evaluation of known deposits rather than on the prognostication of undiscovered deposits. This emphasis on the known deposits renders iron evaluations different than those for base metals, where the emphasis is on the prognostication of undiscovered deposits.

Uranium. Following the pioneering qualitative assessments of uranium by Lang (1958) and Roscoe (1966) and the first quantitative uranium prognostications embodied in the Operation September report of 1972, the Canadian government announced in 1974 the establishment of a Uranium Resource Appraisal Group (URAG). Comprised of geologists, mineral economists and mineral treatment specialists from the Department of Energy, Mines and Resources, URAG was assigned the task of an annual audit of Canada's uranium resources and, by late 1975, had

Table I *Selected examples of Canadian resource assessment studies. The abbreviation "O.F." refers to Geological Survey of Canada Open File reports listed under references.*

Year	Author(s)	Area	Commodities Reported	Method	Form of Results
1958	Lang	Canada	Uranium	Geological	Qualitative
1966	Roscoe	Canada	Uranium Thorium	Geological	Quantitative
1969	Kelly and Sheriff	British Columbia	Various	Geostatistical	Quantitative
1970	Gross	Canada	Iron	Geological	Quantitative
1970	Barry and Freyman	Northern B.C. and Yukon	Various	Subjective probability (Delphi)	Quantitative
1970	De Geoffrey and Wu	Canadian Shield	Various (Dollar values)	Probabilistic	Quantitative
1971	De Geoffrey and Wignall	Grenville Province	Various	Probabilistic	Quantitative
1972	Agterberg et al.	Abitibi District	Copper, zinc	Geostatistical	Quantitative
1972	Azis et al	N. Manitoba	Various	Subjective probability (Delphi)	Quantitative
1973	Derry	Arctic and Sub-Arctic	Cu,Pb,Zn,Au,Fe	Geological	Quantitative
1974	McCartney et al.	British Columbia	Various	Geological	Qualitative
1974	McCartney and Matheson	British Columbia	Various	Geological	Qualitative
1975	Robertson	Ontario	Various	Geological	Qualitative
1977a	E.M.R.	Canada	Cu,Pb,Zn,Mo,Ni	Geological	Quantitative
1977b	E.M.R.	Canada	Fe	Geological	Quantitative
1977	Ruzicka	Canada	Uranium	Geological	Qualitative
1977	O.F. 492	Western Arctic	Various	Geological	Qualitative
1978	Agterberg and Divi	Appalachians	Cu,Pb,Zn	Geostatistical	Quantitative
1978	Sinclair et al.	British Columbia	Various	Geological	Qualitative
1980	O.F. 716	N. Yukon, NWT (Parts of) and Arctic Islands	Various	Geological	Qualitative
1980	O.F. 691	N. Yukon and NWT (Parts of)	Various	Geological	Qualitative
1980	Gale et al.	Manitoba	Massive sulphides	Geological	Qualitative
1981	Findlay et al.	Arctic Islands	Various	Geological	Qualitative
1981	Agterberg et al.	S. District of Keewatin, NWT	Various	Geostatistical	Qualitative
1981	O.F. 760	N. Yukon	Various	Geological	Qualitative
1981	O.F. 786	N. Ellesmere Is.	Various	Geological	Qualitative
1982	Labovitz and Griffiths	Canada	Various (Dollar values)	Geostatistical	Quantitative
in prep.	Sinclair et al.	Yukon	Various	Geological	Qualitative

published a preliminary uranium assessment as of 1974 (E.M.R., 1975). The geological principles used in these assessments were described by Ruzicka (1977), and Martin *et al.* (1977) outlined the quantification procedures used. The basis of URAG's assessments was conceptual models of geological deposit-types, the same principle as that used in base metal and iron prognostications. An important point to note here is that URAG's annual reports (e.g., E.M.R., 1981) present not only prognostications of undiscovered deposits but also evaluations of Canada's known uranium resources in terms of three resource categories (measured, indicated and inferred). Uranium appraisals, in terms of this emphasis, therefore lie between those for base metals (emphasis on prognostication) and those for iron (emphasis on evaluation of known deposits). These annual uranium reports (to be published biennially beginning in 1983), represent the most sophisticated and methodical mineral resource assessment program in Canada.

Current G.S.C. Method—the Conceptual Model

Since 1977, the Geological Survey of Canada has issued a number of Open File publications on the resource potential of several large areas of northern Canada (Fig. 1). These assessments, originated in response to requests from native peoples' organizations and government agencies such as Parks Canada, were prompted by a number of northern land assignment studies. More recently, the G.S.C. has continued this work in the belief that it has potential usefulness in identifying areas for exploration by industry.

The resource evaluation method most widely used in the G.S.C. is based on the principle of conceptual models of selected deposit-types. By this method the common and obvious geological parameters of many deposits of the same type are combined to erect a hypothetical or ideal descriptive and genetic model for each deposit-type. Both regional and local geological features are an integral part of the conceptual model, but it is the former which are used most extensively in mineral resource evaluations. The conceptual models used are usually a combination of those published by other workers plus modifications based on G.S.C.'s mineral deposits geologists' extensive Canadian and world-wide examinations and studies of a variety of deposit-types. Drawing upon this experience, together with information from files of mineral deposits data compilated over many decades (the first G.S.C. Economic Geology Reports, on talc and iron, were pubished in 1926), composite conceptual models are established and then compared with the geology of the area(s) being assessed. The conceptual model approach, the basis of all current

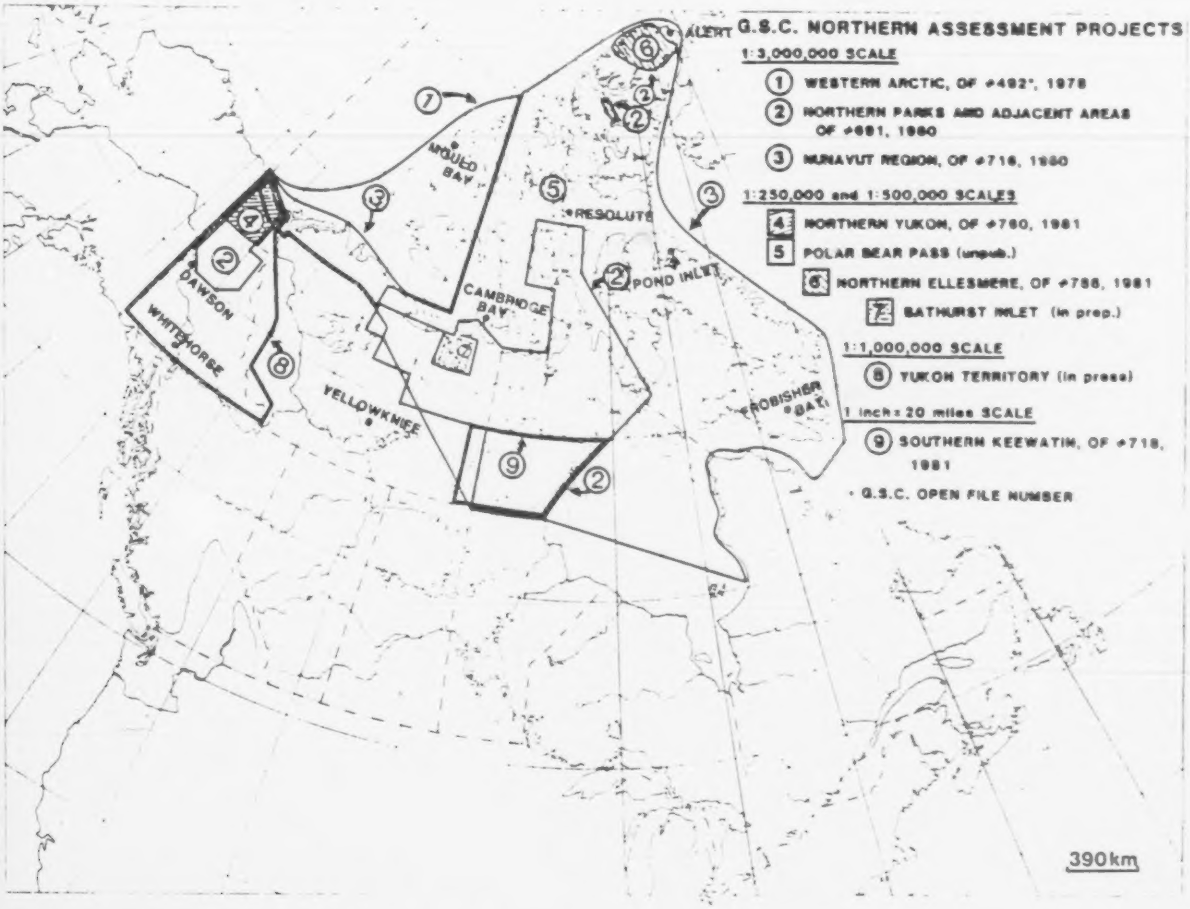

G.S.C. NORTHERN ASSESSMENT PROJECTS
1:3,000,000 SCALE
① WESTERN ARCTIC, OF *492*, 1978
② NORTHERN PARKS AND ADJACENT AREAS OF *681, 1980
③ NUNAVUT REGION, OF *716, 1980
1:250,000 and 1:500,000 SCALES
4 NORTHERN YUKON, OF *760, 1981
5 POLAR BEAR PASS (unpub.)
6 NORTHERN ELLESMERE, OF *788, 1981
7 BATHURST INLET (in prep.)
1:1,000,000 SCALE
⑧ YUKON TERRITORY (in press)
1 inch = 20 miles SCALE
⑨ SOUTHERN KEEWATIN, OF *718, 1981
* G.S.C. OPEN FILE NUMBER
ALERT
MOULD BAY
RESOLUTE
POND INLET
CAMBRIDGE BAY
DAWSON
WHITEHORSE
YELLOWKNIFE
FROBISHER BAY
390km

Figure 1 *Recent Geological Survey of Canada regional resource assessment projects in northern Canada.*

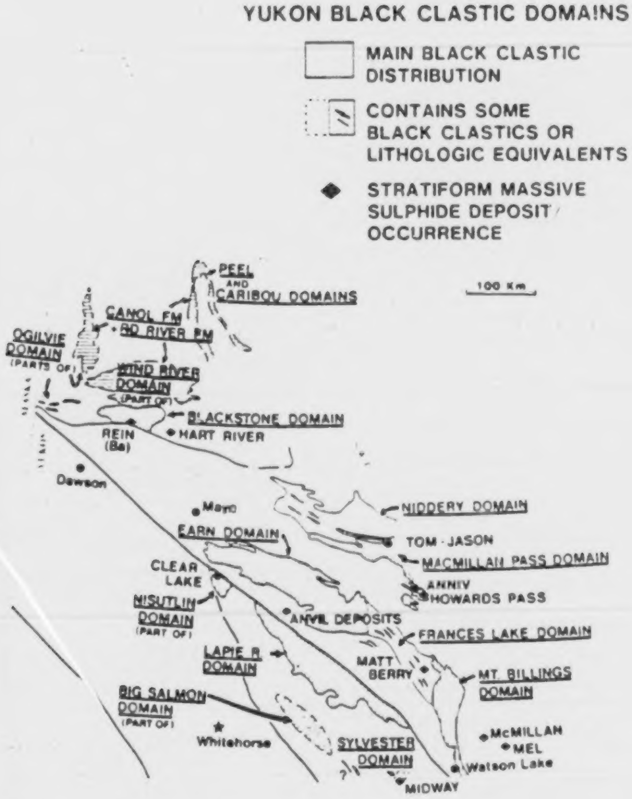

YUKON BLACK CLASTIC DOMAINS
MAIN BLACK CLASTIC DISTRIBUTION
CONTAINS SOME BLACK CLASTICS OR LITHOLOGIC EQUIVALENTS
STRATIFORM MASSIVE SULPHIDE DEPOSIT / OCCURRENCE
100 Km
PEEL AND CARIBOU DOMAINS
CANOL FM
RD RIVER FM
OGILVIE DOMAIN (PARTS OF)
WIND RIVER DOMAIN (PART OF)
BLACKSTONE DOMAIN
REIN (Ba)
HART RIVER
Dawson
Mayo
NIDDERY DOMAIN
TOM - JASON
EARN DOMAIN
MACMILLAN PASS DOMAIN
CLEAR LAKE
ANNIV
HOWARDS PASS
NISUTLIN DOMAIN (PART OF)
ANVIL DEPOSITS
FRANCES LAKE DOMAIN
LAPIE R. DOMAIN
MATT BERRY
MT. BILLINGS DOMAIN
BIG SALMON DOMAIN (PART OF)
Whitehorse
McMILLAN
MEL
SYLVESTER DOMAIN
Watson Lake
MIDWAY

Figure 2 *Yukon assessment domains containing Black Clastic and equivalent lithologies*

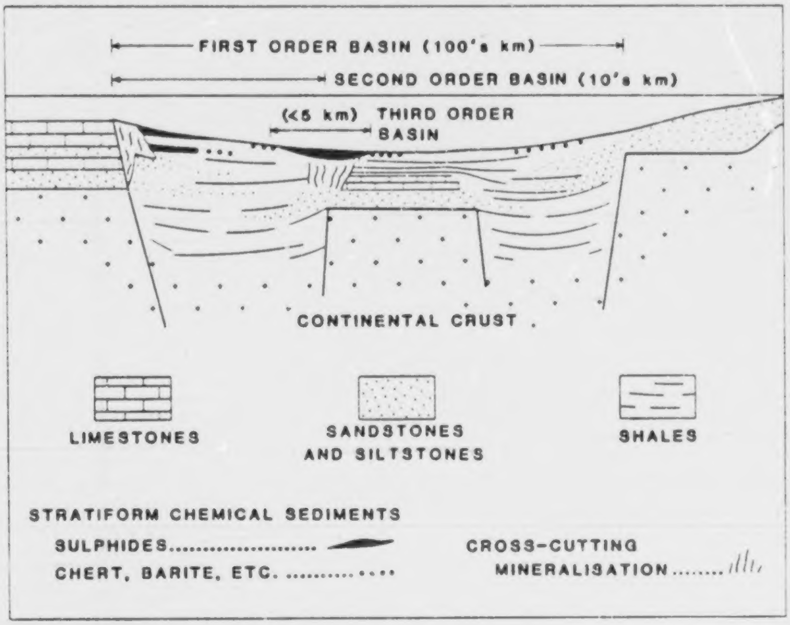

FIRST ORDER BASIN (100's km)
SECOND ORDER BASIN (10's km)
(<5 km) THIRD ORDER BASIN
CONTINENTAL CRUST
LIMESTONES
SANDSTONES AND SILTSTONES
SHALES
STRATIFORM CHEMICAL SEDIMENTS
SULPHIDES
CHERT, BARITE, ETC.
CROSS-CUTTING MINERALISATION

Figure 3 *Composite model of a sediment-hosted submarine exhalative sulphide-barite deposit (modified slightly from Large, 1980).*

G.S.C. base metal, uranium and iron assessments, resembles most closely the *simple subjective* method of Singer and Mosier (1981). Described (Singer and Mosier, 1981, p. 1008) as a method whereby "estimates (are) made directly by one or more individuals based on their experience and knowledge", the *simple subjective* method makes the best use of available expertise, time and data. Furthermore, the resultant product can be easily reported in a manner to suit its ultimate use. In a sense, then, the method probably differs little from the initial phase of many mineral exploration programs, most of which are also the result of intuitive deduction by experienced personnel.

To illustrate the conceptual model method of resource evaluation as currently employed in the G.S.C., the author has selected one deposit-type (sediment-hosted, stratiform lead-zinc type) as it was evaluated in three areas: 1. Yukon Territory; 2. northern Ellesmere Island; 3. northern Baffin Island. These three areas illustrate the range of geological data-bases normally available to geologists performing resource assessments. For example, Yukon Territory is covered by geological maps on several scales, it contains many known deposits of the sediment-hosted type and several large areas within it have been covered by regional geochemical programs. Northern Ellesmere and Baffin Islands have good geological maps only; no mineral occurrences of the type in question have been reported and no regional geochemistry has been done.

Yukon Territory. The first phase of the assessment was to divide the area into geological domains based mainly on structure and stratigraphy. Those domains containing the Devono-Mississippian Black Clastic assemblages (or equivalents) were selected for special study (Fig. 2). The Black Clastic assemblage is known to contain several sediment-hosted stratiform lead-zinc(-barite) deposits, so it is a readily identified target assemblage (e.g., Tom, Jason; see Fig. 2).

Within the Black Clastic assemblage, the

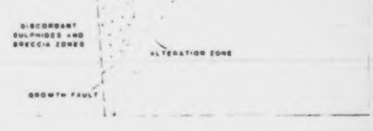

SULPHIDES
BARITE
Fe OXIDES
STRATIFORM SULPHIDES
DISCORDANT SULPHIDES AND BRECCIA ZONES
ALTERATION ZONE
GROWTH FAULT

Figure 4 *Typical regional setting of sediment-hosted submarine exhalative sulphide deposits (modified from Large, 1980).*

main geological characteristics of the target deposit-type (Fig. 3) were sought. Only a few of these characteristics can reasonably be expected to be portrayed on the 1:50,000 to 1:250,000 scale data-base maps normally used in assessing areas this large For example, large syn-sedimentary faults and evidence of exhalative activity (e.g., stratiform barite and/or iron-manganese oxides, chert, etc.) are regarded as positive metallotects. Current knowledge and understanding of this deposit-type (Large, 1980; 1981) indicates that these deposits would fit into a regional pattern in a manner schematically illustrated in Figure 4. Consequently, evidence of the possible existence of second- or third-order basins is sought in geological criteria portrayed on existing geological maps, such as direct observation of syn-sedimentary faults or indirect indicators of the same such as rapid sedimentary facies changes, abrupt variations in thickness of sedimentary units, peculiar breccias which may indicate a fault-scarp talus or sudden changes in depositional environment (e.g., a rapid change from shallow- to deep-water sediments which may indicate graben-like movements).

Table II *Explanation of mineral potential rating categories used in a recent G.S.C. assessment study of Yukon Territory (from Sinclair and Leech, 1982)*

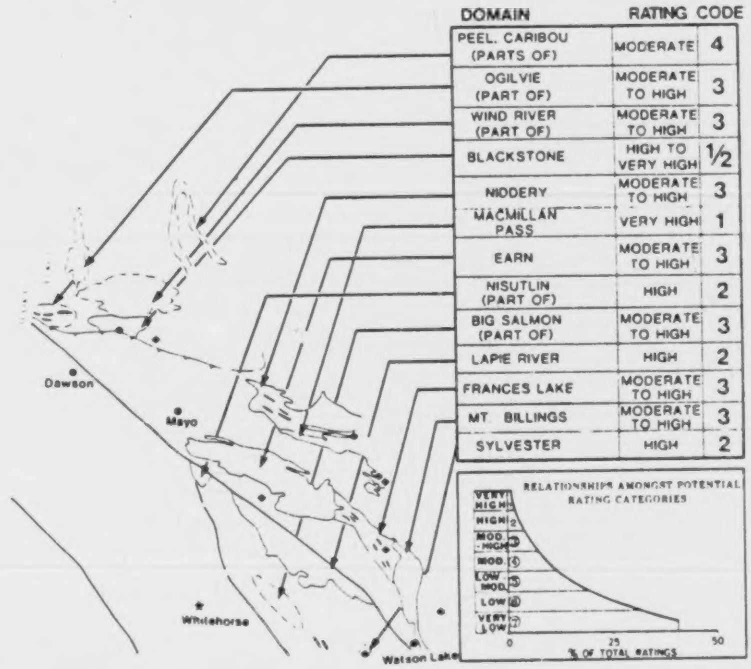
Rating	Criteria
Very high	Geological environment very favourable. Significant deposits present. Additional undiscovered deposits very likely.
High	Geological environment very favourable. Mineral occurrences present but no significant deposits known.
Moderate	Geological environment favourable. Mineral occurrences may or may not be present.
Low	Aspects of the geological environment may be favourable, but limited in scope. Few, if any, mineral occurrences known. Undiscovered deposits unlikely.
Very low	Geological environment unfavourable. No mineral deposits or occurrences known. Undiscovered deposits very unlikely.

Combining all geological and geochemical features in a subjective fashion, a rating is assigned to the domains being assessed. The rating categories range from "very low" to "very high" depending on the number and kinds of metallotects identified in the domain (Table II).

By this method, a subjective assessment of the potential occurrence of stratiform lead-zinc(-barite) deposits in the Black Clastic-bearing domains is achieved and is expressed graphically as shown in Figure 5. Note that the rating categories are more logarithmic than arithmetic in nature, as suggested by the curve in the lower right portion of Figure 5. That is to say, the difference in potential between categories 1 and 2 is much greater than the difference between categories 6 and 7.

Northern Ellesmere Island. For assessment of a proposed national park in this region, (G.S.C., 1981, O.F. 786) the geological base used was that published by Trettin (1971). From the point of view of sediment-hosted lead-zinc deposits, the Hazen Formation was particularly interesting for several reasons: 1. it occurs in an intracratonic basin, the Franklinian Basin (Trettin and Balkwill, 1979); 2. it has been described as having formed in a starved basin during Early and Middle Ordovician time (Trettin, 1971; Trettin and Balkwill, 1979); 3. the lithologic sequence is very similar to that containing the Howard's Pass, Yukon, stratiform lead-zinc deposit which is also contained in a lower Paleozoic restricted basin facies (Gordey, 1980; Gordey *et al.*, 1981). The gradual upward decrease in carbonate and increase in chert content in the Hazen Formation (Trettin, 1971, p. 40) is very similar to that recorded in the Active Member of the Howard's Pass Formation (Morganti, 1981, p. 72). Furthermore, Trettin (1971, p. 40, 44) noted two isolated occurrences of breccia in the Hazen Formation. The sudden appearance of angular, locally-derived breccia within the otherwise fine-grained clastic and chemical sedimentary rocks of a low-energy starved basin regime was regarded by the assessor not only as anomalous but also as possibly indicative of syn-sedimentary faulting. As a consequence of these interpretations, domains containing the Hazen Formation in northern Ellesmere Island were assigned a very high rating potential for sediment-hosted lead-zinc deposits (Sangster, 1981).

Borden Basin, northern Baffin Island. Initiated as an aulacogen in the north Baffin Rift Zone, Borden Basin is regarded as one of several rift, fault-controlled basins developed along the northwestern edge of the



DOMAIN	RATING	CODE
PEEL. CARIBOU (PARTS OF)	MODERATE	4
OGILVIE (PART OF)	MODERATE TO HIGH	3
WIND RIVER (PART OF)	MODERATE TO HIGH	3
BLACKSTONE	HIGH TO VERY HIGH	1/2
NIDDERY	MODERATE TO HIGH	3
MACMILLAN PASS	VERY HIGH	1
EARN	MODERATE TO HIGH	3
NISUTLIN (PART OF)	HIGH	2
BIG SALMON (PART OF)	MODERATE TO HIGH	3
LAPIE RIVER	HIGH	2
FRANCES LAKE	MODERATE TO HIGH	3
MT BILLINGS	MODERATE TO HIGH	3
SYLVESTER	HIGH	2

Figure 5 *Summary of assessment ratings derived for the various Yukon domains containing Black Clastic assemblages and equivalent lithologies.*

Canadian-Greenlandic Shield (Jackson and Iannelli, 1981). Within Borden Basin, syndepositional faulting has had a profound effect on sedimentation resulting in numerous facies changes and wide ranges in thicknesses of all formations (Jackson *et al.*, 1978; Iannelli, 1979). Particularly significant with regard to the perceived potential for stratiform lead-zinc deposits is the faulting which took place during deposition of the Arctic Bay Formation, a locally pyritic shale ranging in thickness from 100 m near the western end of the Rift to more than 1200 m near the eastern end.

Features within Borden Basin, and in particular within the Arctic Bay Formation, considered to be relevant to the possible occurrence of sediment-hosted stratiform lead-zinc deposits are 1) the abundant evidence of syn-sedimentary faulting, particularly during Arctic Bay time; 2) the presence of a series of horsts and grabens in the Basin, equivalent to the second-order basins illustrated in Figure 4 and suggesting, in turn, the possibility of third-order deposit-size basins; 3) a local anomalous geothermal gradient as evidenced by the presence of basalts extruded in the early stages of rifting in the west end of the Basin. All these features combined to impart a very high potential to the Arctic Bay Formation (Sangster, 1981), even in the absence of known mineral occurrences in the unit.

Conclusion

Nation-wide resource assessment studies in Canada probably began in 1958 with Lang's uranium map. Since then various agencies have experimented with a variety of techniques and on a variety of scales. Within the Geological Survey of Canada, however, with more than fifteen years experience in resource assessment methodologies, the most widely used technique is that of the conceptual model. This technique is versatile in that it can be readily adapted to suit a wide range of data bases, time constraints, commodities and presentation formats. It makes extensive use of composite geological models of deposit-types against which is compared the geology of the area being assessed. Some of these assessments are currently being published in the form of Open File assessment reports which typically might contain information such as that listed in Table III. Presented in this manner, the assessment reports may be used for government land use decisions as well as for mineral exploration.

II ? →

Acknowledgements

The author takes this opportunity to thank his colleagues G.A. Gross and V. Ruzicka for their discussions and constructive comments during preparation of this manuscript.

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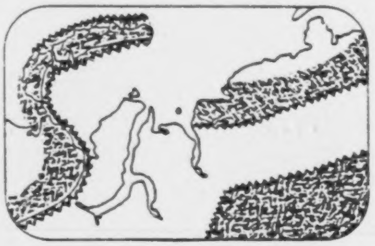

2. Methods of Predictive Metallogeny in the USSR

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Methods of Prediction

Nowadays one of our main geological tasks is prediction of the development of a program for supplying the country with mineral resources. This includes outlining and evaluating promising areas and discovering new types of deposits and ores for rational distribution of mining industries.

There are two main trends in the prediction of mineral deposits in the USSR: predictions based on the results of regional metallogenic studies, and predictions based on statistical-empirical investigations, aided by information about the deposits (data banks) and regional geology with the aid of computers.

The first trend is a traditional one in the USSR. Its fundamentals were laid down by S.S. Smirnov, Yu. A. Bilibin, V.I. Smirnov, P.M. Tatarinov, V.G. Grushevoy, A.I. Semenov, V.A. Kuznetsov, G.A. Tvalchrelidze, I.G. Magakyan and other Soviet scientists. The second trend is now being worked out in various scientific and industrial geological institutions throughout the country. Among well known developments in this latter trend is the "Region" prediction system (devised in the International Scientific Research Institute of Control Programs, Moscow), comparable both in terms of the problems solved and the software of the system to that employed in the "Appalachians" project in Canada. In the "Region" system interaction between the geologist and the computer is of primary importance, as is the choice of prediction variants made on the basis of genetic hypotheses. We shall concentrate here upon the first, metallogenic, trend developed in VSEGEI, the head institution of the USSR Ministry of Geology dealing with regional and predictive metallogenic studies.

Studies in the prediction of mineral resources are carried out in different ways, depending on the final aim. The aims and analytical methods of "special" and "regional" predictive-metallogenic studies are quite distinct. "Special" predictive-metallogenic studies are determined by the necessity to supply the mining and processing industries with ores of a particular composition. This scientific trend of investigation is based on the analysis of distribution patterns of the deposits discovered, on the establishment of the controlling factors of mineralization and, hence, the criteria for prediction (Fig. 1). The above initial data, summarized from all the deposits of the type under consideration, are later employed in the analysis of new territories. As a result, the local areas of promise are outlined and the quantitative evaluation of predictive resources is made. This method has been employed in several areas, e.g., the systems of prediction directed toward supplying the industry of the Kola Peninsula with ferruginous quartzites, manganese oxide ores and copper-nickel ores, supplying the Ural smelters and the copper-molybdenum industrial enterprises of Kazakhstan with copper sulphide ores and supplying Siberian areas with potash salts, etc. The principles and methods of special predictive metallogenic studies are summarized in the book "Kriterii prognoznoi otsenki" (1978).

"Regional" or "combined" predictive metallogenic studies are carried out during the planned geological investigation of Soviet territory. The targets of investigation in this case are areas of various scales: provinces, zones, districts. By these investigations, we hope to determine the whole complex of economic minerals that may be found in the particular territory, to define the main deposit types and to outline and evaluate the promising areas. Predictive-metallogenic studies of this character are based on regional geological research, i.e., geological, geophysical and geochemical survey data. The analysis is based on a classification of zones; established regularities (metallotects) are widely used, e.g., the association of ores with particular zone types, their period of evolution and their geological formations. Accordingly, predictive metallogenic studies presuppose in this case metallogenic division, accompanied by the outlining of types of zones (in space) and stages (in time), subsequent detailed formational analysis and, after the promising mineralization types are defined, the employment of the whole complex of methods of special metallogeny (Fig. 1).

Evaluation of the territories of Karelia and the Kola Peninsula, Timan, the North Urals and the territory along the Baikal-Amur railway (now under construction), for the whole complex of economic minerals can be taken as examples of regional combined predictive metallogenic studies on scales of 1:1,000,000—1:1,500,000. The scientists of VSEGEI took an active part in these programs. The principles and methods of regional predictive-metallogenic studies are summarized in the book "Rudonosnost'i geologichskie formatsii ..." (1981).

"Special" and "regional" metallogeny supplement each other and work most effectively when employed together. As seen from Figure 1, these two scientific trends differ in the sequence of the initial operations during analysis. In the first case we proceed from the deposit type being sought, in the second, from the area being analyzed. In the final stages of analysis, those of outlining the promising areas, evaluating them quantitatively and choosing the work types, special and regional metallogenic methods are analogous.

Quantitative prediction presupposes appraisal of prospective ores or metals in tons, points or conventional units, or by the number of large, medium and small deposits of the type predicted. The categories (1-3) are also mentioned, depending upon the degree to which they were substantiated.

Methods of quantitative prediction, on the whole, are analogous to those employed in Canada and in other countries. "Evaluation by experts" and the method of analogies are most commonly used. In calculating by the method of analogies one defines the specific ore content of a thoroughly examined "standard" territory, very similar to the territory being analyzed, in terms of its geological development, complexes of formations, tectonic setting and time of formation. Then a formula proposed by N.A. Bykhover is used: $Q = KqV$, where Q represents prospective reserves within the zone, V = its geometric characteristics, q = specific ore content of the standard territory and K = coefficient which takes into account the dissimilarity of the territories in some features. In some cases our estimates are based on the area of the promising territory, in other instances we take into account the length of the perimeter of the ore-bearing zone or fracture, and in still other cases we look at the number of promising ore clusters indicated by the intersections of the ore-controlling structures. As for the extensively studied deposit types and territories, a direct calculation method for the resources predicted is used, e.g., one which is based on regression analysis of the relations between resources and the intensity of manifestation of ore-controlling factors. When data on the clarkes of chemical elements and dispersions of their distribution in rocks and soils are available, we can employ one of the geochemical methods of estimation proposed by L.I. Ovchinnikov, E.M. Kvyatkovsky, N.I. Safronov, A.P. Solovov, A.A. Smyslov and others ("Kolichestvennoye prognozirovanie...", 1979).

In the large- and medium-scale metallogenic analysis (1:500,000—1:50,000) the principal structural-material objects of investigation are a formational complex, geological and ore formations and spatial and temporal metallogenic units compatible with them (Table I).

The principle of step-by-step detailing of territory is believed to be a common methodological approach to solving the problems of special and regional metallogeny. The essence of the principle consists in the employment (for the purpose of territory evaluation) of various criteria proceeding from general regional criteria, which allow the rejection of large territories, to more detailed ones which localize the promising areas within the territories outlined earlier. As seen from Figure 1, the basic factors in prediction are the accumulated and generalized data on the classification of zones, geological formations and deposits. Important factors determining the effectiveness of the prediction system under consideration are a complete as possible usage of the data and the employment (during analysis) of information about simi-

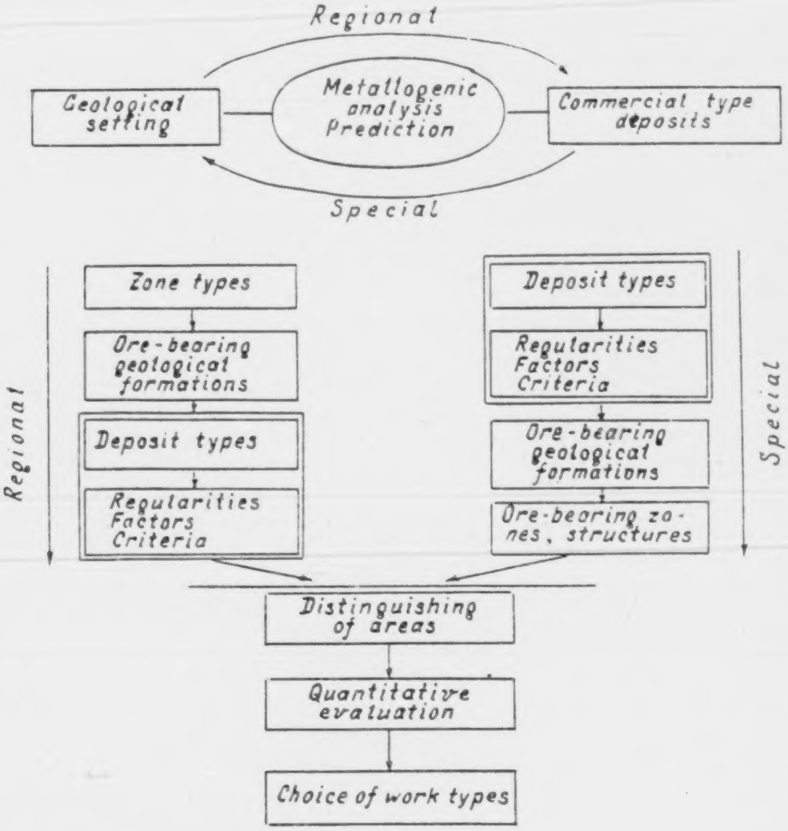
Regional
Geological setting
Metallogenic analysis Prediction
Commercial type deposits
Special
Zone types
Ore-bearing geological formations
Deposit types
Regularities Factors Criteria
Regional
Deposit types
Regularities Factors Criteria
Ore-bearing geological formations
Ore-bearing zones, structures
Special
Distinguishing of areas
Quantitative evaluation
Choice of work types

Figure 1 Succession of operations in regional and special predictive-metallogenic studies.

Table I *Compatibility of structural-material, spatial and temporal metallogenic units*

Mineral formations (substance)	Forms of manifestation (space)	Period of manifestation (time)
Formational complex-regular statistically stable paragenesis of formations, is distinguished by the age- and lateral series of formations	Structural formational zone (in plan), stage (in section) — distribution of a formational complex. Structural-metallogenic zone — area of distribution of mineralization within one complex. In section of stratified formations — structural — metallogenic stage	Stage of tectonic history — separated by intervals of major structural reconstructions — period of emplacement of a formational complex
Geological formation — regular statistically stable paragenesis of rocks. Ore-bearing Geological formation – geological formation with which mineralization is associated in space and time Divided into productive (directly includes mineralization), mother (with associated mineralization but outside the zone and formation) and ore-enclosing ones.	Formational zone (in plan), substage (in section) — distribution of geological formation Metallogenic zone — zone of distribution of ore-bearing geological formation and the associated mineralization	Phase, substage of tectonic history of folded area, platform, region of activization — period of emplacement of a geological formation
Ore formation — regular statistically stable paragenesis of ores characterized by monotype structure (by zoning)	Ore zone — zone of distribution of an ore formation	Stage of mineralization, magmatism, metamorphism, sedimentogenesis — period of emplacement of an ore formation

lar zones, geological formations and ore content in other regions and on other continents. For instance, evaluating the prospects of the Precambrian rocks in the Karelia-Kola region, in particular the zones of greenstone belts of Archean age,we made good use of the experience gained in studies of the troughs on the Ukrainian Shield, Canada and Australia, and in studying the ore content of granitoid formations we used data obtained from "classical" provinces of the Krusne Hory, Cornwall, Southeastern China, Mongolia, etc.

Let us consider briefly the main results of of studies of the ore content studies in metallogenic zones and geological formations, determining local areas for a more detailed prediction and search for minerals.

Types of Structural-Metallogenic Zones

In the last two decades methods of predictive-metallogenic studies in the USSR have changed substantially. The changes were conditioned by the transition from distinguishing zones by the period of their development (cycles, etapes and stages of folded areas, platforms and areas of tectonic-magmatic activization) to distinguishing units on the basis of structure and substance. Accordingly, metallogenic analysis nowadays is based on recognition of zones by series of geological formations, the outlining of ore-bearing formations, the employment of geochemical, mineralogical and geophysical criteria for prediction, analysis of the rhythm, zoning of strata, massifs, zones, etc.

Such a change in orientation was necessitated by the fact that time divisions are sometimes considered to be subjective and are thus a subject of controversy. For instance, consider the Adjar-Trilet Cretaceous-Eocene zone of the Caucasus, represented by tholeiite basalts, andesites, rhyolites succeeded by carbonate-terrigenous rocks and then by alkaline basalts, and andesites with intrusives of gabbrodioritic composition. One group of workers assigns this zone to the rift stage; another group assigns this zone to the early- or late-geosynclinal zone and still another group of geologists assigns it to the secondary-geosynclinal one. But from the viewpoint of predictive evaluation based on rock composition, rhythm and specific features of the deep structure, all the workers agree that the zone looks promising in regard to iron ore, skarn, copper- and polymetallic-pyritic and copper-porphyric deposits.

Classification of structural-metallogenic zones in the USSR was made on the basis of composition of formations, sequence of their formation and alternation in section and structure. A total of 87 zone types has been distinguished, including 50 stratified ones (23 sedimentary amagmatic and 27 sedimentary-volcanogenic), 21 zones with predominant development of "cutting" intrusive and metasomatic formations emplaced along the fractures, 13 zones of high grade metamorphic complexes and 3 zones of weathering crusts of specific composition, which are subsequently subdivided by mineral composition into subtypes. A brief characterization of all the zones and their ore content is given in the book "Rudonosnost'i i geologicheskie formatsii...", 1981). As an example, we can enumerate the outlined zones composed of stratified sedimentary and volcanogenic formations, which are frequently represented by rocks metamorphosed to albite-epidote or locally to amphibolite facies. Traditionally, those zones are considered early geosynclinal. Nine such zones have been recognized in the USSR (Fig. 2), each differing in a set of formations and ore content.

Mafic, poorly differentiated zones (Fig. 2) are characterized by the fact that the initial volcanics developed in them belong to the undifferentiated formation of sodic basalts, with a scarce occurrence of differentiated components, sodic basalts and liparites. On the peripheries of the zones the volcanics are replaced by siliceous-carbonate and terrigenous strata. In the axial parts of the troughs sulphur-pyrite deposits and small copper-pyrite occurrences are common; on the periphery there are deposits of iron-ore siliceous formations and manganese braunite-hausmannite-rhodonitic siliceous formations, as well as Mo-V-slates.

In the most typical case, mafic differentiated zones (Fig. 2) occur in the Urals (many copper-pyritic and iron ore skarn deposits associate with them). They are characterized by multiple rhythmic alternation of the following formations: trachybasalts—sodic basalts—sodic basalts and liparites—basalt-andesitic formation. Volcanics closely alternate with a slate formation or siliceous, siliceous-tuffogenic and terrigenous-carbonate units.

Alkaline-mafic zones (Fig. 2) are noted for their potash basalt-trachyte formation which plays the leading role among the volcanic rocks composing the zone. Mafic-salic zones are characteristic of "secondary" eugeosynclinal troughs and are defined by extensive development of sodic basalt formation with which polymetal pyritic deposits associate spatially and genetically.

Among the zones in which volcanics are practically lacking, a number of types have been recognized by predominant constituents: terrigenous, carbonate, siliceous and black slate zones. For the accompanying mineralization, natural series are outlined here which reflect the association of ore types with geological formation: phosphorites, hematite-quartz, braunite-hausmannite--rhodonite ores and others associated with siliceous formations: gold ore with black slate, lead-zinc with black slate; bauxites, barite-lead-zinc ores and others with carbonate reef formations.

Of primary importance in the analysis of the real ore content of structural-metallogenic zones is quantitative correlation between formations composing the zone, their thickness, order of alternation in space and time, complete or incomplete development and composition of the basement. The following are some examples.

Copper pyrite deposits are common in geosynclinal zones with normal homodrome trend of volcanism (a sequence from basic to acid), with a great variety of rocks in some rhythms, from basalts to quartz keratophyres and albitophyres. A vertical section displays an upward change of mineralization, with an increasing role of zinc and lead in their higher stages.

Copper-nickel deposits of the Pechenga type are characteristic of riftogenic zones of mafic composition, but with the antidrome trend of volcanism, from tholeiitic basalts to picrites or komatiites.

In orogenic regions the basement composition acquires great importance for prediction. The deposits of copper-porphyric formations are emplaced, as a rule, in structures on a mafic basement which have the homodrome trend of volcanism evolving from andesites to dacites and quartz porphyries. The tin ore deposits of rhyolite and silicate-cassiterite formations are characteristic of orogenic zones with antidrome trend observed in large rhythms and homodrome trends in small ones, and are emplaced in the troughs on the salic basement.

When analyzing formation series of structural-metallogenic zones, one can find a number of common features in localization of mineralization:

1. In comparing various cases of succession in rock evolution and the associated ore formations, one can observe a certain correlation: the wider the evolutionary range of substance composition in the course of rock development, the more varied the composition of ore mineral parageneses will be.

Deposits constituting "long" evolutionary mineral series are associated with the "long" evolutionary series of magmatic rocks, with many stages of mineralization overlapping (and, as a consequence, with distinct zoning). The more compositionally homogenous deposits with less pronounced differentiation of products during the mineralizing process associate with a "short" evolutionary series. For example, tin-tungsten greisen deposits, characterized by a distinct step-by-step process, are

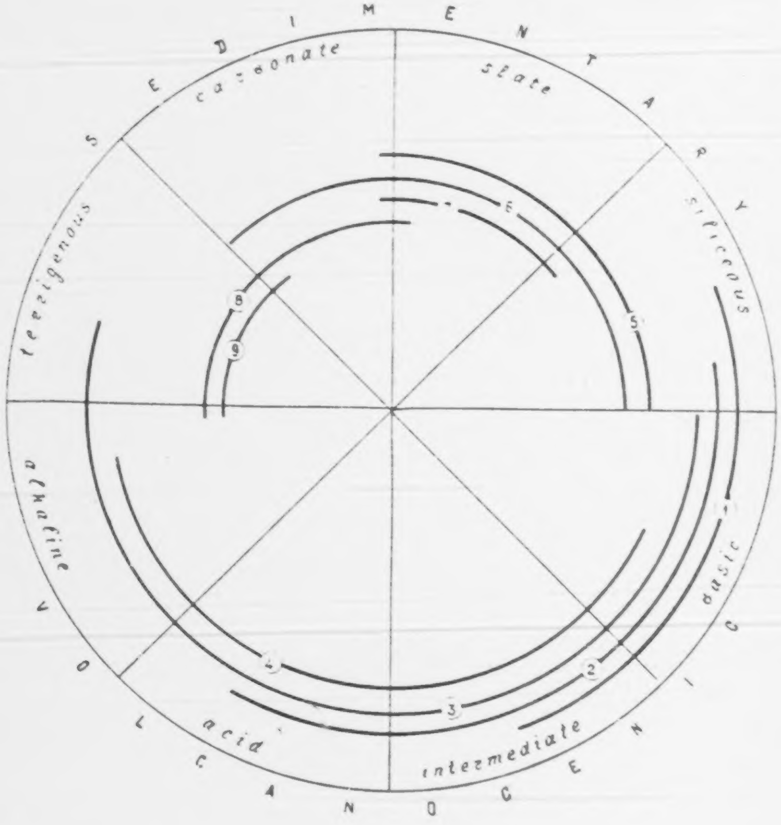

Figure 2 Types of structural-metallogenic zones of volcanogenic-sedimentary and sedimentary troughs of the folded areas in the Phanerozoic: 1. mafic poorly-differentiated; typical mineralization: Cu, Zn, Fe, Mn, phosphorites, Tyan-Shan' (Kirghizian) type. 2. mafic differentiated, Fe, Cu, Zn Uralian (Tagil-Magnitogorsk) type; 3. alkaline-mafic, Mn, Fe, Cu; Eastern-Kamchatka type; 4. mafic-salic, Pb, Zn, Cu; Rudny Altai type; 5. siliceous slate, Fe, Mn, phosphorites; Far East (Udsk-Shantarsk) type; 6. siliceous-slate-carbonate, Fe, Mn, Zn, Pb, barite, phosphorites, Kazakhstan (Atasui) type; 7. slate, Cu, Zn, Pb, Co, Caucasian (Filizchaisky) type; 8. terrigenous-carbonate, Pb, Zn, Au, bauxites, magnesite, Fe, Hg, fluorite, South Kazakhstan (Karatau) type. 9. terrigenous Au, Cu, Zn, Pb, Sb, Northeast (Verkhoyansk) type.

believed to form in association with a "long" evolutionary series of magmatism; molybdenum-tungsten deposits, known for less distinct step-by-step processes, associate with a "short" evolutionary series.

The diamond and chromite deposits ("late magmatic") form in association with "short" evolutionary magmatic series and occur in isolation, without displaying close association with other mineralization types.

In contrast, a wide range of deposits of chromite ("early magmatic"), platinum and titanomagnetite is found to be associated with "long" evolutionary series of rocks (ultra- basic → basic → acid) of the Bushveld complex type. A typical example of "long" evolutionary series is the development of ultrabasic-alkaline intrusives of the "central" type, rich in a variety of minerals (Fe, apatite, phlogopite, occasionally rare metals and rare earths).

2. In comparing various cases of succession in the development of rocks and taking into consideration how widespread some varieties of rock are, we come to a conclusion about the great importance of breaks in the evolutionary processes of rock formation.

From a comparison of different ore districts, we find that the majority of deposits, exogenous and endogenous, were emplaced during the time intervals when the processes of sedimentation, volcanism or magmatism in the given zone (or district) were not active at all, or were extremely slow. The analysis shows that the most promising appear to be those structures which display multiple rhythm in section, stratigraphic breaks, omission of some horizons or a sharp decrease in the thickness of strata synchronous with ore deposition. In the areas where magmatic rocks are widespread, breaks in the rhythms are equally favourable, and these are identified by the appearance of dykes, regionally distributed metasomatites, etc.

This correlation, established in the USSR by A.D. Arkhangelsky, D.G. Sapozhnikov, N.M. Strakhov and others, for many sedimentary deposits (phosphorites, bauxites, manganese and iron ores, Pb-Zn-mineralizations), is observed also in the analysis of deposits emplaced by endogenous processes: gold-silver, copper-molybdenum, pyritic and others which are confined to localities where the section displays omission or great reduction of volcanic units synchronous with mineralization.

Ore Content In Geological Formations

After we have defined the zone type and possible ore content of the territory under consideration we proceed to the solution of local problems: the distinguishing of ore-bearing geological formations, an operation that localizes the areas of promise.

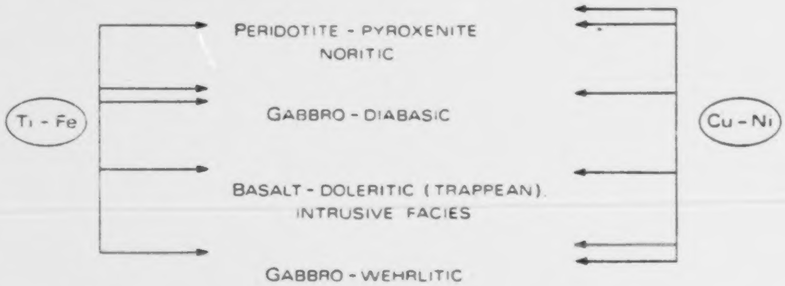

Figure 3 Relation between scales of mineralization and geological formations of various compositions. Double arrows indicate formations with which the largest ore concentrations associate.

Formational analysis resulting in recognition of specialized ore-bearing formations, among which productive, mother and enclosing rocks are singled out ("Kriterii rudonosnosti...", 1978), has developed rapidly in the USSR in recent decades, and has been linked with the solution of problems of prediction. As a result, we have systematized the geological formations and characterized the ore content of 59 sedimentary, 45 magmatic, 24 metamorphic and 15 hydrothermal-metasomatic formations, as well as 14 formations of weathering crusts and products of their direct redeposition, including placers ("Rudonost'i geologicheskie formatsii...", 1981). It is necessary to emphasize, however, that the potential ore content is realized only in certain cases, i.e., when a formation is localized within a required zone type of certain age, and when a favourable combination of stratified, "cutting" intrusive, metamorphic, metasomatic or weathering crust formations is observed. It is these circumstances, as well as several structural features (which define to what extent the ore deposition system is closed or open), that determine whether the mineralization will be a large economic one or will be represented only by small occurrences on which there is no need to waste money. For example, iron-titanium mineralization and copper-nickel mineralization in the USSR display associations with the same formations: peridotite- pyroxenite-noritic, gabbro-diabasic, basalt-doleritic and gabbro-wehrlitic (Fig. 3). Large iron-titanium deposits, however, associate only with gabbro-diabases (Kusin deposit), whereas important copper-nickel deposits associate with peridotite-pyroxenite-noritic (Monchegorsk) and gabbro-wehrlitic formations (Pechenga).

Along with the geological formations, 150 ore formations of main economic deposit types have been recognized. It was found here that in order to work out a system of prediction this number of ore formations was insufficient. For such ore formations as siliceous-hematitic, manganese braunite-hausmannitic, skarn iron ore, high almina nepheline-feldspathic, rare metal-pegmatitic, copper-molybdenum porphyric and many others, we had to single out subformations which would differ in the geolgical setting in which mineralization is manifested, in association with various geological formations and, respectively, with various criteria for prediction. For instance, the sulphide copper-nickel deposits usually are assigned to one genetic type and one ore formation. Nevertheless, for purposes of prediction it is necessary to distinguish here at least 5 subformations ("Kriterii rudonosti...", 1978). These subformations actually represent a series of ore objects associated with different geological formations. The extreme members of this series are the ore-bearing, deep-seated, layered peridotite-pyroxenite-noritic plutons (Monchegorsk type) on one side, and on the other side ore-bearing minor intrusives of olivinite-gabbroic, gabbro-wehrlitic formations, localized among volcanogenic and sedimentary rocks near the surface (Norilsk, Pechenga type).

With this diversity of ore formations and subformations, the following appears to be promising: first, the distinguishing of common regional criteria, valid for the whole group of ore formations and subformations, and individual local criteria for every subtype. Second, the distinguishing of series of formations and subformations which differ in composition, structure and geological setting in which mineralization is manifested and, consequently, in the criteria for prediction.

In the above example of copper-nickel mineralization the outlined series reflect the substantiated change in geological conditions in which ultrabasic magmatism and mineralization manifest themselves: depth, the scale of the magmatism, how open or closed the system of ore deposition was, specific effect on physical-chemical characteristics of the environment (sulphur, reducers, etc.). Accordingly, the Monchegorsk type arises at depth, in a comparatively closed system, in conditions of slight specific interaction between melts, solutions and the environment. In contrast, the Pechenga type deposits form near the the surface, in an open system, in conditions of melts and solutions intensively interacting with the wallrocks rich in sulphur and other reducers.

The diversity of ore formations and subformations indicates that for the purpose of prediction it is advisable to devise models of manifestation of various genetic mineralization types whose number will be considerably smaller than the number of ore formations and subformations.

It is of paramount importance in prediction to take into account the "absolute" and "relative" (in the course of a megacycle, cycle, rhythm) period of the emplacement of geological and ore formations. For each type of mineral deposit one or two, (rarely three) epochs of the maximal manifestation of the given type of mineralization can be outlined. Such epochs might be global and regional. In the European and Asiatic parts of the USSR one can observe two maxima of phosphorite deposition: the Late Riphean-Ordovician (750-450 Ma) and the Upper Cretaceous-Pleistocene (after 80 Ma). It is characteristic that the Permian phosphorites, which are so typical of other regions of the world (the Cordillera), are represented in the USSR only by small occurrences in the fore-Urals and in the Caucasus.

As for the manganese deposits in the USSR, three main epochs of most intensive deposition have been established: the Vendian-Cambrian and Silurian-Devonian, in association with siliceous and carbonate formations, and the Oligocene (Chiatura, Nicopol), in association with calcareous-arenaceous-argillaceous formations. The ore-bearing productive epochs could be global—connected with general changes in atmosphere, hydrosphere, lithosphere (e.g., for phosphorite, manganese, coal, ferruginous quartzites, etc.), or regional—connected with the peculiarities in geologic history of individual regions. Thus the distribution of Cu-Pb-Zn-mineralization in the mid-Devonian is characteristic of the European continent and contiguous territories known for the extensive development of Hercynian tectogenesis. In Eastern Siberia, the Altai-Sayan area's most intensive emplacement of copper and polymetal stratiform mineralization falls in the Riphean. Equally, the maximum emplacement of tin, copper-molybdenum and a number of other endogenous deposits was substantially different in the Mediterranean and Pacific ocean belts and also within the Russian and Siberian platforms.

In some cases, geological and ore formations of the same type but of different ages are noted for characteristic features of mineral composition and minor elements, which need to be taken into consideration during prediction. Thus, when defining the practical importance of ferruginous quartzite zones we should take into account the quantitative magnetite/hematite ratio in the ores, a ratio which naturally decreases with time, down to the emplacement of pure hematitic quartzites of Riphean age.

These examples indicate the necessity of accumulating more data on the evolution of geological and ore formations in the history of the Earth. It is these new data that will enable us to make various corrections and to introduce some coefficients during estimation of prospective resources by the method of analogy with the districts that have been thoroughly studied.

The formational research carried out in recent years has allowed the establishment of qualitative and quantitative relations between mineralization scales and geological formations. One of the main conclusions is that the rock of economic interest is the one that is a constituent of a particular geological formation, developed within the zone of a certain type and during the favourable time intervals, rather than merely a rock of a certain composition and texture.

Further perfection of the system of predictive studies requires the extension of the theoretical basis for metallogeny and the employment of general correlations in geologic history established in other disciplines, e.g., in tectonics, stratigraphy and geomorphology. Of great importance for the analysis of ore deposition is the Walther-Golovchinsky facies law, which reveals the unity of interrelation of rocks in time and space during sedimentation. In the processes of ore deposition, a similar dependence can constantly be observed, which is expressed in the principle of similarity and in the geogenetic law. The principle of similarity reflects the fundamental similarity of the ore zoning in various spatial units, from metallogenic provinces to ore fields and deposits. The geogenetic law defines the similarity in the development of ore deposition processes on different time scales. The general sequence in the evolution of formations in geologic history is manifested in the individual evolutionary history of particular deposits, as if in a diminished form, on the scale of mineral assemblages and individual minerals.

In devising geological-genetic models of ore formations and ore-bearing zones for the purpose of prediction of mineralization at depth, one should use the "geoid" and Curie-Shafranovsky principle of symmetry. The "geoid" principle is the empirically established regularity of manifestation of the most intensive mineralization in the Earth's crust near the geoid surface. The crust here plays the role of regional base-level of erosion, the place where oxidation-reduction processes accompanying ore-deposition are believed to change, etc. The geoid principle requires the employment (in metallogenic analysis) of data on paleotopography at the period of ore-deposition, on the extent of ruggedness of the relief and absolute heights. The principle also requires determination of the surfaces of peneplains.

The P. Curie principle, detailed by I.I. Shafranovsky for geological objects, states that the real symmetry of the forming geological bodies reflects the symmetry of the environment. It follows from this that in the gravitational field of the Earth the inner structure (zoning) of various ore-bearing objects being formed is always characterized by unidirectional vertical and bilateral (planal) or central horizontal symmetry. This principle accounts for many features of mineralization distribution in stratiform and "cutting" geological formations.

Among the applied aspects in the further development of theory and methods of predictive metallogenic studies are included the following:

1. improvement in the methods of quantitative prediction
2. ability to work out the criteria for prediction of large and very large deposits and ore districts
3. discovery of a rational complex of methods of prediction for new deposit types

These objectives are believed to be common in the geological investigations of all countries, and their solution requires generalization and analysis of data on the metallogenic zone types, geological formations and distribution patterns of deposits in all the continents of the world.

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3. An Investigation of the Estimation Process of Predictive Metallogeny

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Introduction

The substance of this paper is relevant to the subject of predictive metallogeny only to the extent that a quantitative prediction of some resultant of metallogenesis is a primary objective. Identification of prediction as a primary goal imposes on the geologist or team of geologists involved in prediction the necessity of integrating available geodata, data which are often sparse and of poor quality, with respect to those concepts of metallogenesis that can be related to some quantity, e.g., number of deposits or quantity of metal.

For the remainder of this paper, I shall refer to predictive metallogeny as the estimation of mineral endowment, meaning the number of deposits or the tonnage of metal that occurs in the region, given some minimum size of accumulation (deposit), minimum concentration (grade) and maximum depth of occurrence. Because of the often great uncertainty about mineral endowment, the estimate of interest is taken to be a probability distribution for the endowment of the region.

Methods of predictive metallogeny understandably vary with 1) the amount and the quality of geodata, 2) the data available on mineral discoveries and resources of the region, and 3) the time and human resources provided for analysis. Consider prediction for a region for which the geodata that are available on the entire region are at the reconnaissance level. These data may include geologic maps, aeromagnetic maps, gravity maps, geochemical surveys and maps of mineral occurrence. Exploration may have identified prospects and ore bodies. There may be a few producing mines. Even so, the region is not considered to be well explored, and resource data are either too meagre or are too restricted geographically to support the estimation by multivariate statistical methods of a quantitative relationship between geodata and a quantity of mineral occurrence. This circumstance is one which is frequently encountered in regions which generally are considered to have high potential for mineral occurrence. Regions in Canada and Mexico, for example, would be accommodated by this description.

Given these circumstances, a quantitative estimate of mineral endowment may be pursued by two basically different approaches:

1. The selection of other, well explored areas (control areas) which are geologically similar to the region of interest, and the identification on these control areas of multivariate statistical relationships which can be used to infer mineral endowment.
2. The identification of one or more geological experts who, by virtue of rich experience in exploration on other areas, specific knowledge of the geology of the area of interest and an understanding of concepts and principles of metallogeny are capable of providing subjective estimates in probability terms of the mineral endowment of the area of interest.

Each of these approaches has its advantages and disadvantages; the basis for selecting one of them over the other will not be considered here. The assumption, rather, is made that the latter of these approaches has been selected. Given that assumption, the central issue of this paper is the methodology to support the use of observed geodata by the geologist to describe a probability distribution for a region's mineral endowment. The emphasis of the paper is on the *process* or *methodology* of subjective estimation of an uncertain quantity, *mineral endowment*.

While it is commonly understood and acknowledged that estimation of mineral endowment is difficult, it is my perception that the difficulty is greater than is commonly perceived. This difficulty arises from three major sources: limitations of geoscience, insufficient geodata and inadequate methodology for probability estimation of mineral endowment.

The use of geodata to infer the presence of a mineral deposit when there is no direct evidence of the presence of the deposit requires a model of the relationship between either the geodata and mineral occurrence or of the processes implied by the geodata and mineral occurrence. Such a model can be basically empirical, reflecting mainly observed associations, or it may be based upon genetic relations.

Every geologist is aware of the limitations of his science to explain unequivocably all mineral occurrences. Often there is more than one theory for the genesis of a particular deposit. Furthermore, experienced geologists have witnessed the revision of theories as more data become available and as our knowledge of the earth increases.

The limitations of geoscience referred to above include this lack of an unequivocal explanation. But, with respect to the estimation of mineral endowment, these limitations take on a considerably greater dimension. This greater dimension reflects the lack of geoscience, as it is generally understood and practiced, of a scale (magnitude) dimension with regard to mineral occurrence. It is one thing to recognize the necessity for the sequential operation of a sequence of earth processes to form a mineral deposit of a specified kind, but it is quite another to be able to relate the spatial dimensions and intensities of these processes to the *number* of deposits – to the *total quantity of metal* – within the region. It is the latter of these acts that poses great difficulty to the geologist.

The next section discusses generally major methodologies for the subjective estimation of mineral endowment when the estimate is a product of geological analysis and is a probability distribution. Following this general description, a case study is described which allowed for the comparison of two different methodologies for the probabilistic estimation of the uranium endowment of the San Juan Basin of New Mexico. Finally, some thoughts are presented of an improved methodology for the estimation of mineral endowment of frontier regions.

Conventional Methods of Subjective Geological Analysis and Probability Estimation

Subjective probability methods for the estimation of mineral or energy endowment have been classified as implicit or explicit (Harris, 1977, 1982). These terms refer to the way in which probability and endowment are related by the methodology to geology. The conventional approach to geologic analysis and subjective probability estimation is of the implicit type.

In the implicit methodology the geologist examines all relevant geodata and resources data, if such are available, and after due integration of these data and reflection upon the geoscience of this particular mode of occurrence, he selects either percentiles or statistics from which the parameters of the endowment distribution may be estimated (Fig. 1). As is evident, the process of estimation by the implicit methodology is relatively unstructured and relies heavily upon intuitive processes.

In its simplest form, this methodology produces a probability for mineral endowment or one of the components of endowment, e.g., number of deposits (see Harris and Carrigan, 1981; Singer and Ovenshine, 1979). A more complex form of implicit estimation was employed by the U.S. Department of Energy (1980) to make the NURE estimates of the uranium endowment of the United States. The NURE methodology decomposes uranium endowment (E) to five components (A, F, T, G, and P_0):

A = size of favourable area
F = fraction of favourable area underlain by mineralization
T = tonnage of mineralized material per square mile of favourable area
G = average grade of mineralized material
P_0 = probability for at least one deposit having at least 10 tons of U_3O_8 given a cutoff grade of .01% uranium

Although the original design of the appraisal methodology, as shown in Figure 1, treated A as a random variable, as the methodology was applied, only the most likely estimate of A was employed. Subsequent to their geological investigations, geologists provide most likely plus 5th and 95th percentile estimates for each of A, F, T and G. They also provide a single point estimate of P_0. Distributions are fitted to A, F, T and G and these distributions and P_0 are combined appropriately to yield a probability distribution for uranium endowment (see Fig. 2).

Some Deficiencies of Implicit Estimation
Implicit appraisals of mineral endowment rely upon the geologist's qualitative geologic analysis to infer from geologic evidence to potential mineral occurrence. Uncertainties about the evidence and about inference are the bases for subjective probabilities about mineral endowment, or about its components. This is a highly intuitive and judgemental process. The geoscience relations employed by geologists and the relative weights given by them to various kinds of geologic evidence by this procedure are not identified or documented. Similarly, the roles played by perceived geoscience-endowment relations and observed geodata in the uncertainties which are reflected in the subjective probabilities are not identified. Both the geologic and probability analyses can be decribed as implicitly made. Difficulties in mentally performing simultaneous geologic and probability analyses create needs for 1) using geoscience in a way that diminishes the biases due to heuristics of subjective assessment, 2) preventing purposeful hedging, 3) documenting the estimation procedure and 4) promoting thorough data integration.

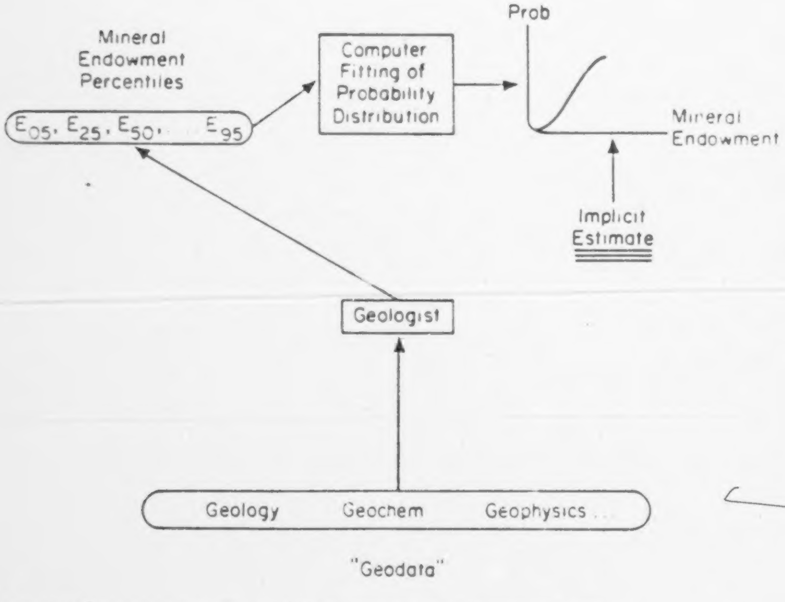

Mineral Endowment Percentiles
E_{05}, E_{25}, E_{50}, E_{95}
Computer Fitting of Probability Distribution
Prob
Mineral Endowment
Implicit Estimate
Geologist
Geology
Geochem
Geophysics ...
"Geodata"

Figure 1 *Conventional subjective probability estimation (implicit geological analysis).*

Heuristics and Bias. Given the complexity of the real world, our limited understanding and our insufficient data, the inclination to employ a loose, intuitive estimation of the probability for a stated level of endowment is understandable; however, some observations and laboratory experiments suggest that intuitive estimation may produce descriptions that have some undesirable characteristics, at least when estimation is routinely made. Overall, these studies (Tversky and Kahneman, 1972, 1974; Alpert and Raiffa, 1969; Pickhardt and Wallace, 1974) suggest that geologists believe they have more knowledge about the event than they actually possess. Generally, the subjective probability distribution is only about one-half as broad as it should be.

Subjective distributions that are too narrow may result when the event being estimated is a compound event, because of the difficulty encountered by intuitive processes in perceiving the many combinations of the components of the event that can result in extreme values. A seemingly reasonable proposition is that forcing the geologist to decompose the estimation process, although more difficult to do, should result in a more complete capturing of the possible outcomes. Of course, employing such a procedure is contingent upon the ability to decompose and reconstitute the compound event in the proper manner. In practice, this can be very difficult when due consideration is given to both the physical and probabilistic dimensions. The construction and use of a geologic decision model is an attempt to decompose the estimation activity and to formalize geoscience of mineral endowment. Formalizing geoscience into a geological decision model forces the geologist to critically evaluate geoscience as it relates to mineral endowment. Such an experience identifies weaknesses or problems that can be supressed by implicit estimation. Furthermore, the experience of formally estimating the probabilities for the earth processes forces the geologist to interpret and integrate geologic data. Without using a formalized decision model, some of this interpretation and integration may be bypassed.

Hedging. Another issue which bears upon the selection of an appraisal methodology is the desire for and ability to produce estimates that are not knowingly and purposefully biased. When geologists consider geology implicitly, it is very difficult for them to erase from their minds previously made estimates and the opinions of others.

The fact that deposits have not yet been found in a unit may downgrade the "gut feelings" for the potential of the region more than is indicated by the geology of the region. The converse may be the case for a rich region. Or, geologists may feel that they are doing society a favour by providing conservative estimates on the grounds that it is always better to be pleasantly surprised than occasionally disappointed. When this desire for conservatism is very strong it can lead to absurd results. For example, Harris and Carrigan (1981) observed that the cumulative effect over all areas of a conservative bias by a geologist was a probability distribution for the aggregate of areas for which the 5th percentile endowment was less than known reserves plus cumulative production. Not only is this result impossible in view of known information, it also contradicts the geologist's general impression of endowment, as informally stated in conversation. For whatever motivations, a geologist appraising endowment implicitly is afforded abundant opportunity to hedge the estimate. An appraisal system which requires the geologist to use a formalized geologic decision model can reduce considerably the opportunity to hedge an estimate.

Credibility and Track Record. Subjectively made resource appraisals often suffer lack of credibility because they may not be reproducible and they do not provide the data and computational algorithm employed in making the appraisal. The use of an appraisal system does not mitigate fully this problem, for it too is subjective in nature. However, a geologic decision model does provide a description of the logic sequence and the computational procedure. This may ease these criticisms. Of course, the design of the model itself may invite other, more specific, criticisms. Consequently, this issue and capability should not be oversold.

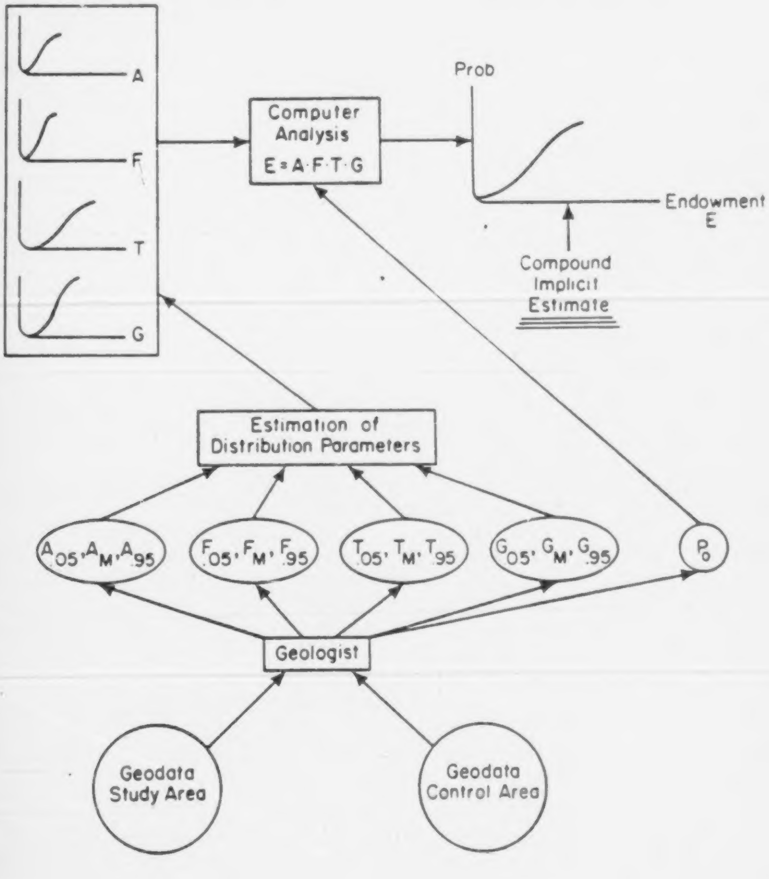


Figure 2 *Implicit methodology of U.S. Department of Energy - NURE.*

Rigor of Analysis. Finally, a motivation for abandoning implicit estimation for the formalizing of geoscience into a geologic decision model is the learning benefit of modelling. Formalizing geoscience forces the geologist to critically examine our science as it relates to the estimation of endowment. Such an experience identifies "fuzzy" concepts and thinking, and problem areas which could otherwise be suppressed or "glossed over". Furthermore, subsequent use of the decision model requires the geologist to more rigorously interpret and integrate geodata. Some of this critical thinking and data interpretation and integration would probably be bypassed if implicit analysis were employed.

Explicit Estimation: Formalized Geologic Inference and Probability Estimation

Explicit estimation of the probability distribution for mineral endowment requires computing the probabilities for endowment from the probabilities for states of those earth processes or geologic conditions which, according to geoscience, dictate the magnitude of endowment. Consequently, explicit estimation requires 1) a specification of geoscience as a decision structure, 2) either observations on geology or probabilities for states of earth processes or geologic conditions of the decision structure and 3) an algorithm for the computation of probabilities for endowment, given the geological observations or geological probabilities.

There are two recently developed approaches which strive to implement geoscience by first identifying the relevant interrelations of processes and geologic conditions and then formally stating these relations as a decision structure. For the moment, these two approaches are referred to simply as A and B (Fig. 3). While A and B are similar in that they both employ geoscience and a formal decision structure, they differ greatly in many other respects. Only one of these is identified here: mode of data use and integration. Figure 3 is a schematic representation of these two approaches, highlighting differences in use and integration of geodata. The schematic diagrams are overly simplified in that they do not show the differences that exist in the design, structure and function of decision analysis. This is purposefully done so as to expose a basic difference, which is both philosophical and methodological, between approaches A and B.

While both approaches formalize geoscience, the philosophy of approach B is that analyses of geodata should be quantitative, i.e., subjective geologic analysis of data is purposefully avoided. In this approach the various forms of geodata are each quantified to binary or ternary form, and these data are submitted directly to decision analysis. Approach B requires that these various kinds of quantified geodata be integrated through quantitative relations (equations) involving the binary or ternary variables, and that this be done within the decision module. Once the decision module has been constructed and is ready for use, the geologists who use it to make estimates function passively in that they do not perform geologic analyses or integrate geodata.

The philosophy represented by approach A runs counter to that of B; namely, the quantifying to a binary or ternary scheme of geodata fails to capture much of the information present in the geodata, and the subsequent integration of such quantified geodata by strictly quantitative relations falls far short of the information captured, integrated and employed by the mental processes of the geologist. This approach requires the geologist to play the active role of analyzing and integrating—through the practice of conventional geoscience—the information present in the various kinds of geodata when considered collectively. Only after analysis and integration of these data does the geologist use the decision model. This is done by answering questions about the states of processes or geologic conditions of the decision model; all answers, which are subjective probabilities, are made only after completion of the analysis and integration of the basic geodata.

Those who favour approach B would defend their choice by the fact that it is an objective geologic analysis. They may argue further that only by excluding the subjective analysis of geologists can one avoid the variations in estimates among geologists and the biases due to the the psychometric issues. Those favouring approach A would argue that simplistic coding (binary or ternary) of geodata and simplistic integration of data by quantitative relations may combine data but cannot, at least at present, achieve the same levels of information relevant to geoscience as is achieved by the integration which takes place in the mind of an expert and experienced geologist.

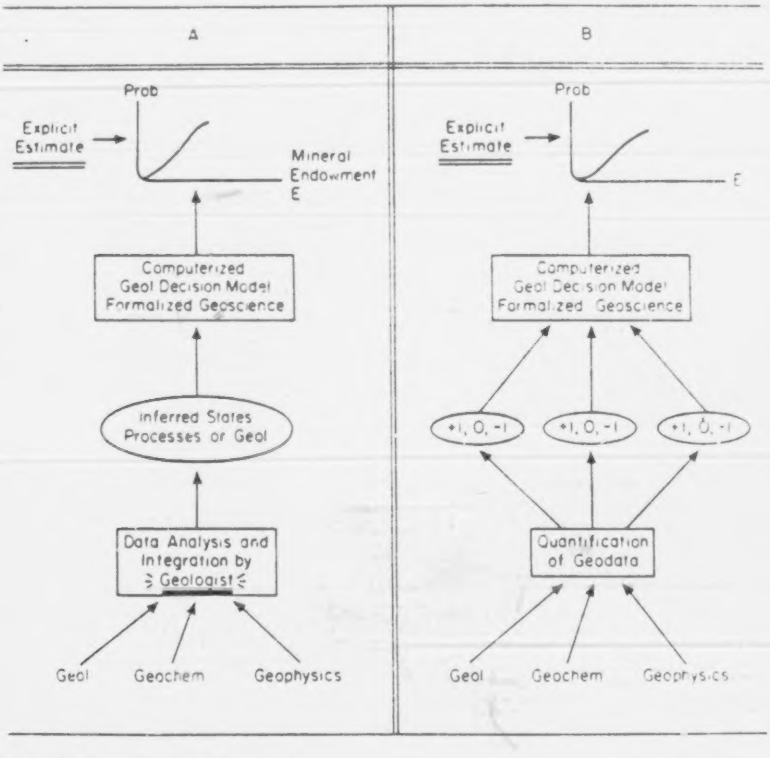

A
B
Prob
Explicit Estimate
Mineral Endowment E
Computerized Geol Decision Model Formalized Geoscience
Inferred States Processes or Geol
Data Analysis and Integration by Geologist
Geol
Geochem
Geophysics
Prob
Explicit Estimate
E
Computerized Geol Decision Model Formalized Geoscience
+1, 0, -1
+1, 0, -1
+1, 0, -1
Quantification of Geodata
Geol
Geochem
Geophysics

Figure 3 *Two approaches to formalizing geoscience for endowment estimation.*

In a broad sense, then, approach B formalizes geoscience and strives for a strictly quantitative use of geodata by this formalized geoscience, while approach A formalizes geoscience as part of a system in which the geologist plays an active role in the analysis and integration of geodata as a prerequisite to the use of decision analysis. As implied in earlier comments, differences in these two approaches are far greater than this basic difference in use and integration may suggest. While Figure 3 shows A and B to be similar in that each has a decision model, these models differ greatly in design and function. These differences have been ignored in this discussion on perspective so as to examine the "big picture" of the use in a system of the geologist, geoscience and geodata.

Methodology of the U.S. Geological Survey: Approach B. Approach B has been pioneered by the U.S. Geological Survey. This methodology brings together three separate efforts, some of which have been in development for several years: characteristic analysis (Botbol, 1971; Botbol *et al.*, 1978), genetic modelling of uranium environments (Finch *et al.*, 1980) and decision analysis (McCammon, 1980).

Characteristic analysis was demonstrated (Botbol, 1971) as a means for quantitatively describing how typical each of a number of characteristics (stratigraphic, mineralogic, geochemical, structural, etc.) is of a set of mining districts. As initially demonstrated, a tableau (matrix) was constructed which showed for each district the presence, denoted by the integer 1 or the absence (0), of each characteristic in each of the districts. Figure 4, which is a specific schematic diagram of the U.S.G.S. methodology, shows the ternary quantification of information on three maps (mudstone/sandstone, alteration and geochemical); for a given cell (map subdivision) each attribute is represented by +1 if present, -1 if absent and 0 if nonobservable. The idea of the attribute matrix derives from characteristic analysis; however, instead of analyzing this matrix for characteristics, the matrix is analyzed by logic circuits which combine attributes in ways that are indicated by genetic models. The design of the logical framework is a result of the construction of genetic models and the identification of those geologic data that are reflective of genetic processes. The result of analyzing the attributes matrix by logic circuits is a new matrix of ternary data in which the data represent genetic factors for each cell. The genetic factors are weighted and combined in a linear equation to yield a measure of favourability for a cell. The final step, which is not indicated on Figure 4, is to convert the measures of favourability to a probability for the occurrence of a deposit within the cell. McCammon (1980) describes how this conversion could be made by strictly objective statistical analysis, given that sufficient data on control areas are available, or by subjective means. However, this part of the methodology has not yet been demonstrated.

Geoscience, including concepts of metallogeny, plays major roles at two levels. First, it is the basis for the construction of the genetic model. Then, given the genetic model, geoscience is used to identify those geologic circumstances and geodata that give evidence of the processes of the genetic model. The logic circuits simply serve as a directory for the combination of the ternary data to reflect genetic factors. Once the model is constructed, the geologist is not an active component in the estimation of endowment for a region.

The Arizona Appraisal System: Approach A. Approach A has been developed and demonstrated in two independent research programs. One of these took place at the University of Arizona (Harris and Carrigan, 1981), where a probabilistic endowment appraisal system, which is based upon the formalization of geologic decisions, was developed and demonstrated on the San Juan Basin of New Mexico. The other research program was conducted at the Stanford Research Institute, where a decision model and extensive supportive software, referred to as *Prospector*, have been developed (Duda *et al.*, 1976; Duda *et al.*, 1977; Hart *et al.*, 1978a, 1978b). Both of these systems employ an inference net as a device to structure formally the

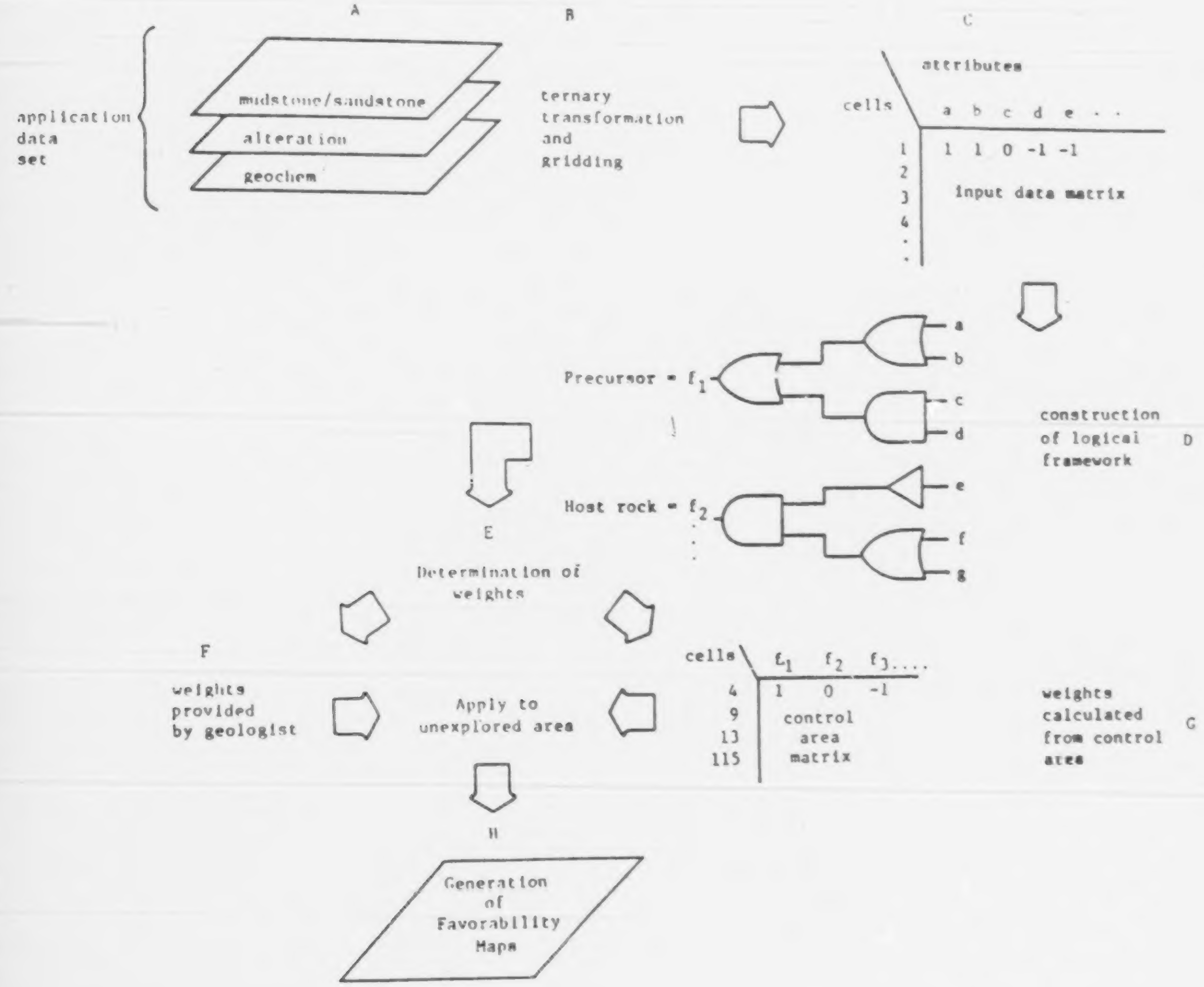

A
B
C
application data set
mudstone/sandstone
alteration
geochem
ternary transformation and gridding
attributes
cells
a b c d e . .
1
2
3
4
1 1 0 -1 -1
input data matrix
Precursor = f_1
a
b
c
d
construction of logical framework
D
Host rock = f_2
e
f
g
E
Determination of weights
F
weights provided by geologist
Apply to unexplored area
cells
f_1 f_2 f_3....
4
9
13
115
1 0 -1
control area matrix
weights calculated from control area
G
H
Generation of Favorability Maps

Figure 4 *Flowchart showing steps for generating favourability maps (McCammon, 1980, p. 22).*

geoscience and decision structure of the geologist. Of these two systems, only the Arizona system has actually been employed to estimate mineral endowment of a large region. In a subsequent section of this paper use of the Arizona system to estimate uranium endowment of the San Juan Basin of New Mexico is described.

Figure 5 provides a schematic overview of the components of the Arizona appraisal system. The items in the heavily outlined boxes are the active components of the system. The items in the circles are either outputs or inputs. The active components perform computations, decisions or analyses. These components include the geologist involved in the appraisal of the mineral endowment of a region; a computerized geologic decision model (this component consists of the formalized geoscience of uranium cast as an interactive computer program); and a synthesis computer program (this combines output from the decision model with other information and computes the probability distribution for U_3O_8).

The use by a geologist of an appraisal system that has already been constructed, calibrated and readied consists of providing subjective probabilities for the states of the geologic conditions and processes that make up the geologic decision model of the system. Thus, as depicted in Figure 5, the geologist processs geologic evidence to probabilistic statements about the states of processes or conditions that comprise the decision model. Table I is an example of the input prepared by a geologist for a region of the San Juan Basin of New Mexico. This table shows probability index numbers, which are probabilities multiplied by 1000. The appraisal system processes these statements to yield the probability distribution for quantity of U_3O_8.

The foregoing description provided an overview of the nature of the appraisal system and of how it is used. As indicated, a geologic decision model is an essential component of the system. Because of the importance of the geologic decision model and because of its interest to the geologist, a description of the structure of the model and the nature of its functions are provided here. By necessity, this description is very general and abridged. For a more detailed and technical description, the reader is referred to the research reports submitted to the U.S. Department of Energy (Harris and Carrigan, 1980).

The structure of the geologic decision model is illustrated in Figure 6. At the bottom of this figure there are three branch-type diagrams (inference nets), one for

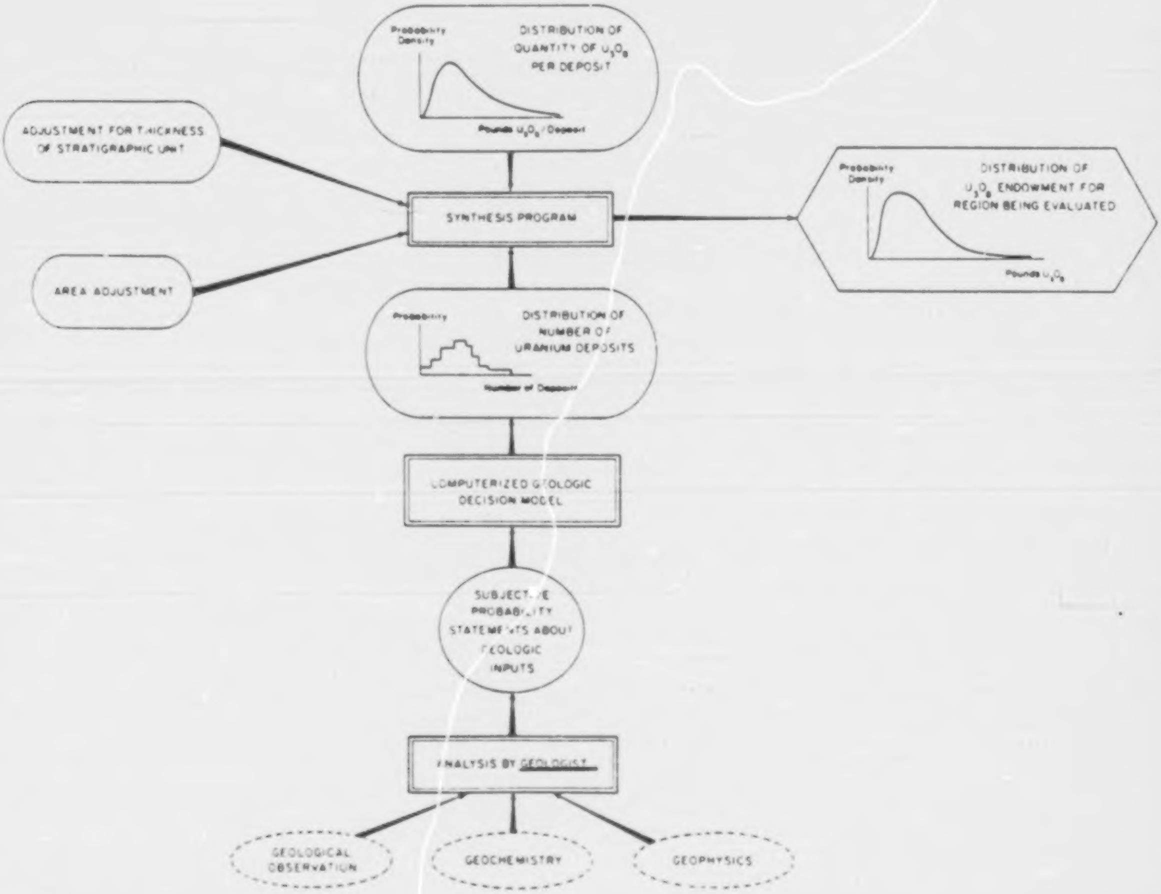

Probability Density
DISTRIBUTION OF QUANTITY OF U_3O_8 PER DEPOSIT
Pounds U_3O_8 / Deposit
ADJUSTMENT FOR THICKNESS OF STRATIGRAPHIC UNIT
SYNTHESIS PROGRAM
Probability Density
DISTRIBUTION OF U_3O_8 ENDOWMENT FOR REGION BEING EVALUATED
Pounds U_3O_8
AREA ADJUSTMENT
Probability
DISTRIBUTION OF NUMBER OF URANIUM DEPOSITS
Number of Deposits
COMPUTERIZED GEOLOGIC DECISION MODEL
SUBJECTIVE PROBABILITY STATEMENTS ABOUT GEOLOGIC INPUTS
ANALYSIS BY GEOLOGIST
GEOLOGICAL OBSERVATION
GEOCHEMISTRY
GEOPHYSICS

Figure 5 *Schematic representation of the endowment appraisal system (Harris and Carrigan, 1980).*

Table I *Subjective Probability Index Numbers*

Geologist: Curly
Horizon: Westwater Canyon/Brushy Basin Members
(excludes Jackpile) Typical Geologic Section

Processes and States	Probability Index Numbers
Leach Source-Transportation Factors	
Extra Basinal Factors	
Extra Basinal Source Rock	
Weathering	
adequate	990
inadequate	10
Size of Source Area	
adequate	990
inadequate	10
Ppm Soluble U_3O_8	
<2	50
2 → 4	450
>4	500
Source Rock Lithology	
crystalline — mafic	100
crystalline — felsic	400
sedimentary — feldspathic	200
tuffaceous	100
sedimentary — other	200
Transportation Characteristics	
Distance Transported	
great	600
short	400
Volume of Transporting Fluids	
large	950
moderate	49
small	1
Intra Basinal Factors	
Intra Basinal Source Rock	
Leaching	
adequate	900
inadequate	100
Volume of Source Rock	
large	950
moderate	49
small	1
Ppm Soluble U_3O_8	
<2	5
2 → 4	195
>4	800
Source Rock Type	
tuffaceous	400
quartzose	99
carbonate	1
feldspathic	500
Transportation Characteristics	
Distance Transported	
great	100
short	900
Volume of Transporting Fluids	
large	950
moderate	49
small	1
Leach Source-Transportation Factors (Cont'd.)	
Intra Basinal Factors (Cont'd.)	
Deposition-Mineralization Factors	
Mineralization Characteristics	
Uranium Anomalies	
Abundance	
abundant	800
moderate	150
sparse	50
Intensity	
high grade	900
medium grade	90
low grade	10
Reducing Agent Characteristics	
Reducing Agent Type	
humate	800
vegetal	199
H_2S	1
Amount of Reducing Agents	
abundant	800
moderate	150
sparse	50
Geochemical Cell Characteristics	
Solution Access	
excellent	700
intermediate	200
poor	100
Reprecipitation Conditions	
excellent	700
intermediate	200
poor	100
Primary Mineralization	
Meteoric Waters	
high u	800
medium u	150
low u	50
Compaction Fluids	
high u	800
medium u	150
low u	50
Depositional site Characteristics	
Climate	
favorable	800
unfavorable	200
Depositional Environment	
fluvial	997
lacustrine	1
marine	1
eolian	1
Living Organisms	
abundant	800
moderate	150
sparse	50
Duration Characteristics	
Duration	
adequate	900
inadequate	100
Rate of Deposition	
rapid	850
moderate	100
slow	50
Host Rock Characteristics	
Facies Changes	
favorable	800
unfavorable	200

Leach Source-Transportation Factors (Cont'd.)
Intra Basinal Factors (Cont'd.)

Premeability-Porosity	
Degree of Fracturing	
abundant	100
moderate	200
sparse	700
Cementation	
tight	100
moderate	200
loose	700
Sandstone Shale Ratios	
favorable	800
unfavorable	200
Post Depositional Factors	
Secondary Enrichment	
Access of Oxidizing Solutions	
adequate	800
inadequate	200
Reprecipitation Conditions	
adequate	800
inadequate	200
Degree of Preservation	
Effects of Oxidizing Solutions	
major destruction	100
moderate destruction	200
negligible destruction	700
Amount of Reductant	
adequate	800
inadequate	200

Source: Harris and Carrigan, 1980.

Table II *Probabilities for States of the Major Processes*

State of Process	Process Identification		
	ST[1]	DM[1]	PD[1]
Excellent	0.89136586	0.32869540	0.35840000
Intermediate	0.10786639	0.42641618	0.21760000
Poor	0.00076775	0.24488841	0.42400000

Geologist: Curly
Horizon: #9/8 Westwater Canyon/Brushy Basin Members
(excludes Jackpile)
Typical geologic section

[1] ST is the Source-Transportation major process.
DM is the Deposition-Mineralization major process.
PD is the Post Depositional major process.

Source: Harris and Carrigan, 1980.

each of three major processes: source-transportation (ST), depositional-mineralization (DM) and post depositional (PD). These nets are a partial formalization of the geoscience of the geologist, for they show cause and effect relations of the important processes. Figure 7 shows an actual net constructed by one of the participants in the study. Each net consists of three separate nets, one for each of the major processes. While an inference net shows the identity and interrelations of processes, it says nothing about the effect of intensity or level of a process on the state of a higher level process. Therefore, to complete the formalization of the geoscience of uranium endowment, the geologist provides a scheme that relates intensities (states) of minor processes to higher level processes. This scheme (directory) is shown as a double-ringed component of Figure 6, between the inference nets and computational algorithm A. Probabilities for the states of the major processes are the output of the computational algorithm. Table II shows this output, given the sue states for each of the three major processes.

The component in Figure 5 referred to as the synthesis program takes as inputs the thickness of the stratigraphic unit being evaluated, the area underlain by the stratigraphic unit, the probability distribution for number of deposits (which was computed by the geologic decision model) for an area of standardized dimensions (reference area), the probability distribution for tonnage of uranium per deposit and adjustment relations for thickness and area. Given these inputs, the synthesis program computes a probability distribution for the quantity of uranium contained by that stratigraphic unit within the region under evaluation.

Selected Comments. It is useful here to recall the perspective initially established of two general approaches to the formalizing of geoscience and their use in the appraisal of mineral endowment. The methodology developed by Harris and Carrigan is representative of one of these: the geologist performs analysis and integration of various kinds of geodata on relatively large areas and then makes probability statements about the states of the processes of the inference net (formalized geoscience); these probabilities are processed to yield a probability distribution for number of deposits for each area. This approach relies heavily upon geologic expertise in two ways, other than identifying the genetic concepts: 1) the linkage of geoscience to endowment and 2) the integration of geodata and the assessment of subjective probabilities about the geologic conditions and processes of the decision model. In this approach, the geologist plays an active part in evaluation by performing the data analysis and integration. In other words, this methodology must rely heavily upon subjective judgements of geologists even apart from the formalizing geoscience. To some this is seen as a liability because of its subjectivity, while to others it is seen as an asset because of its flexibility in integrating various kinds of information.

One appealing feature of the methodology developed by the U.S. Geological survey – Approach B – is that apart from identifying the genetic concepts (geoscience) and the data to support its use, the methodology is basically one of quantitative procedures and quantified geodata. Use of an existing model does not require subjective analysis of the geodata. Application of the model to evaluate the degree of association of an unknown region to the control cells is objective and produces a quantitative measure of this association. Everything else being equal, objectivity is preferred to subjectivity. To some degree, everything else may not be equal, even for use, as distinct from construction, of a model. This statement has particular relevance if the geologist's judgement is used to convert the degree of association – computed by the USGS model – to probability. Constructing a probability dimension for the estimates in this fashion must raise the question of, why? If probability ultimately is to be a judgement call, then asking the geologist to make that judgement about a synthetic measure like f, the measure of degree of association with control cells, seems like questionable procedure. Why not allow the geologist to estimate probability of occurrence as a result of reviewing the familiar (real) geodata? Furthermore, even if the geologist can provide these probabilities, the possibility of heuristic bias may cast some doubt upon the credibility of the estimates, particularly if the probabilities were to be for number of deposits instead of for the presence of at least one deposit. The number of deposits is a complex function terms of the various geologic factors which influence it and which would be considered by the geologist in providing estimates of it. Therefore, asking the geologist to provide probability estimates about this quantity, given only f, provides little support to the

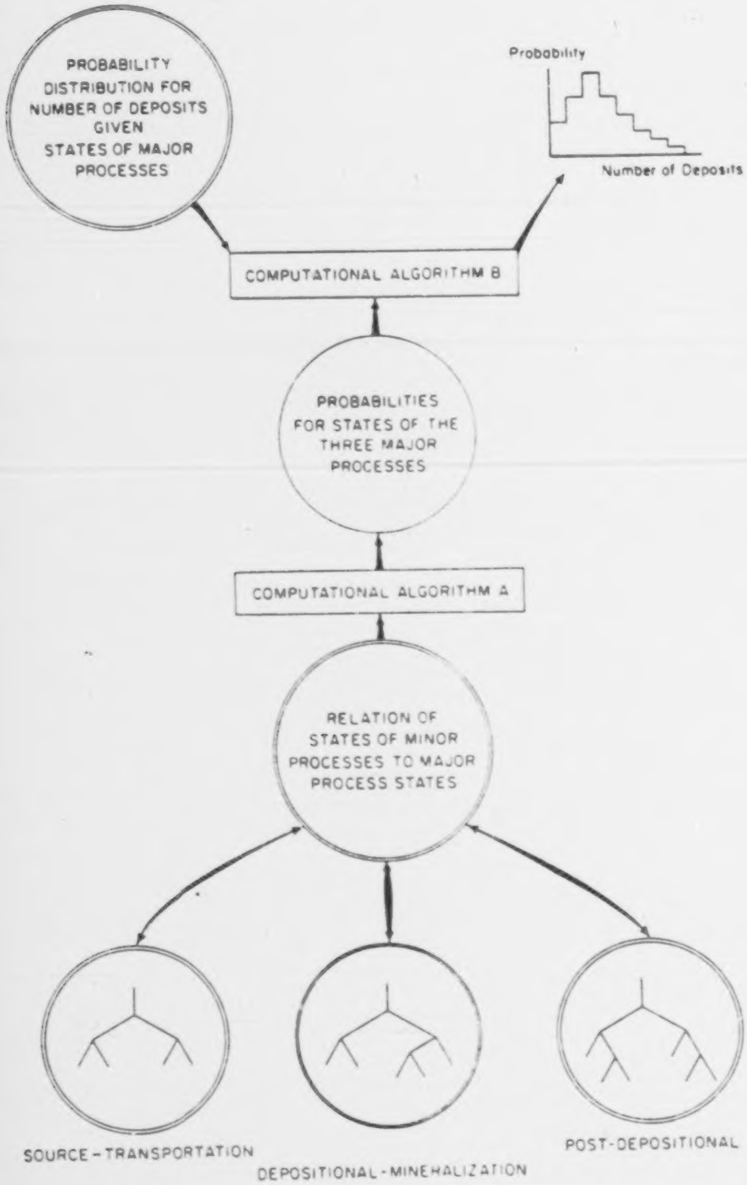

PROBABILITY DISTRIBUTION FOR NUMBER OF DEPOSITS GIVEN STATES OF MAJOR PROCESSES
Probability
Number of Deposits
COMPUTATIONAL ALGORITHM B
PROBABILITIES FOR STATES OF THE THREE MAJOR PROCESSES
COMPUTATIONAL ALGORITHM A
RELATION OF STATES OF MINOR PROCESSES TO MAJOR PROCESS STATES
SOURCE-TRANSPORTATION
DEPOSITIONAL-MINERALIZATION
POST-DEPOSITIONAL

Figure 6 *Structure of the geologic decision model (Harris and Carrigan, 1980)*

Table III *Stratigraphic Units and Partitions Selected for Endowment Appraisal*

Unit	Number of Partitions
San Jose Formation	3
Nacimiento/Animas Formation	2
Ojo Alamo Formation	2
Fruitland Formation	2
Menefee Formation	2
Dakota Sandstone	6
Burro Canyon Formation	3
Jackpile Bed	3
Westwater Canyon/Brushy Basin	8
Recapture Member	4
Saltwash Member	3
Todilto Limestone	5
Chinle Formation	2
Cutler/Abo Formation	3
Madera Limestone	2

Source: Harris and Carrigan, 1980.

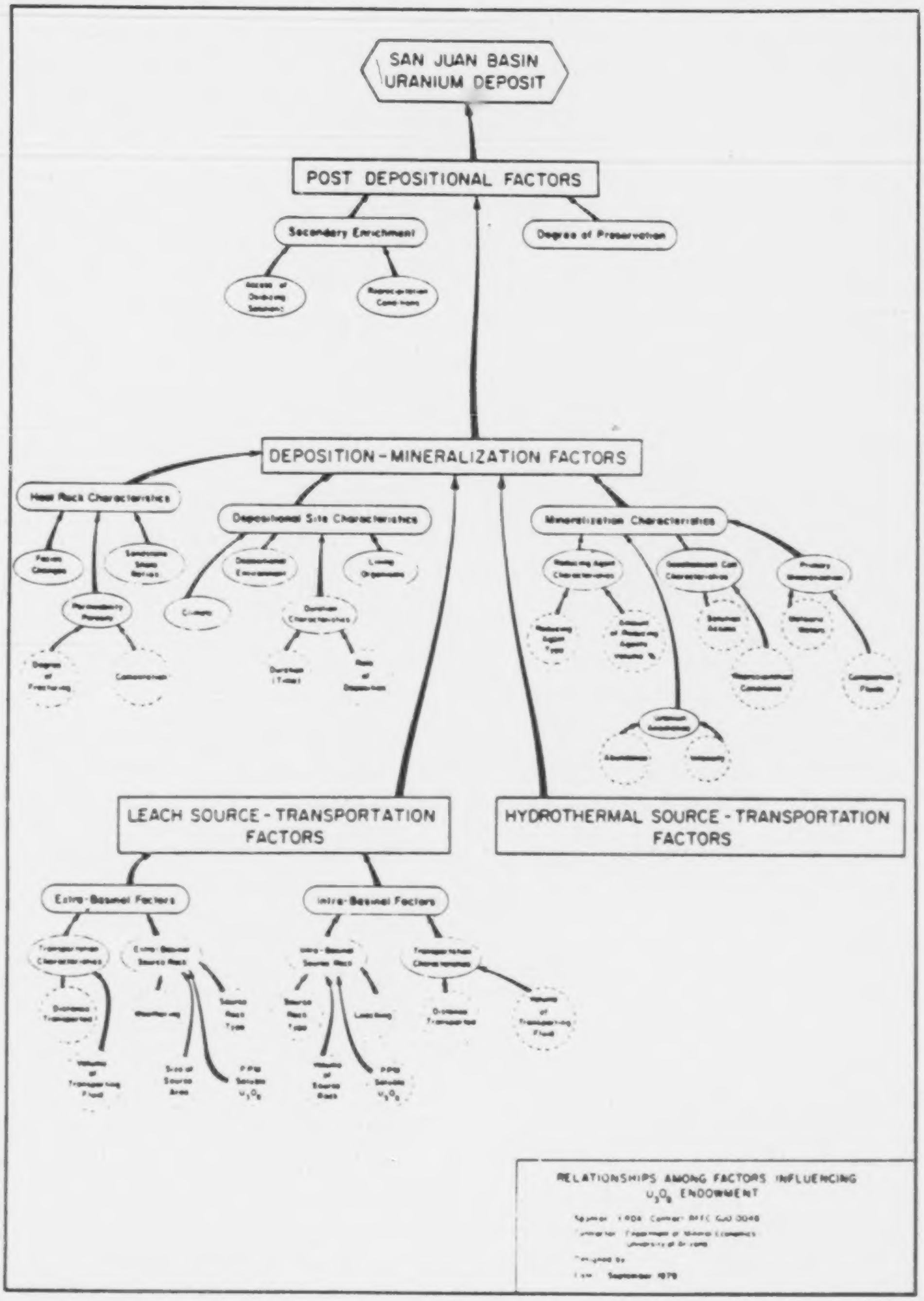

SAN JUAN BASIN URANIUM DEPOSIT
POST DEPOSITIONAL FACTORS
Secondary Enrichment
Degree of Preservation
Access of Oxidizing Solutions
Reprecipitation Conditions
DEPOSITION - MINERALIZATION FACTORS
Host Rock Characteristics
Facies Changes
Sandstone Shale Ratios
Permeability Porosity
Degree of Fracturing
Cementation
Depositional Site Characteristics
Depositional Environment
Living Organisms
Climate
Duration Characteristics
Duration (Time)
Rate of Deposition
Mineralization Characteristics
Reducing Agent Characteristics
Geochemical Cell Characteristics
Primary Mineralization
Reducing Agent Type
Amount of Reducing Agents Volume %
LEACH SOURCE - TRANSPORTATION FACTORS
HYDROTHERMAL SOURCE - TRANSPORTATION FACTORS
Extra-Basinal Factors
Intra-Basinal Factors
Transportation Characteristics
Extra-Basinal Source Rock
Distance Transported
Weathering
Source Rock Type
Volume of Transporting Fluid
Size of Source Area
PPM Soluble U3O8
Intra-Basinal Source Rock
Leaching
Volume of Source Rock
RELATIONSHIPS AMONG FACTORS INFLUENCING U3O8 ENDOWMENT
September 1979

Figure 7 *Completed inference net of participant Curly (Harris and Carrigan, 1980).*

reasoning processes. Given such a circumstance, he or she may be forced to rely heavily upon heuristics, which have been found to lead to bias in the probability distribution.

In order for the methodology developed by the U.S. Geological Survey to be extended so that it estimates endowment—instead of describing only degree of association - it is applied to small cells; otherwise, geology is not effectively represented or used in determining mineral density. But, some factors that influence the level of endowment of a region can best be perceived and described for large regions. Furthermore, for some data, e.g., geophysics, pattern of anomaly and its location *vis-a-vis* other factors may be far more important than a simple description of presence or absence. The point to be made here is that the use of small cells may carry two costs, one being simply the increased time required to assess a large number of cells; the other one is the cost of information lost by using cell sizes so small that the unit of observation is not easily associated with the large-scale geologic factors that have affected endowment. But, employing large cells may make a ternary data scheme inadequate because it does not carry dimensional information. One must wonder about the cost of information lost due to use of a binary or ternary data scheme. Of course, this must be weighed against the benefits of simultaneous consideration of great amounts of data permitted by this approach.

Finally, what about the state of indeterminacy that is represented by zero in the ternary scheme? Geologists commonly are unable to determine presence or absence from direct observation, but are also influenced by the indirect evidence offered from other observations and from Geoscience in general? What is lost when indeterminacy is declared for this circumstance?

A question to be pondered by those studying methodology is, how do the gains of objectivity promoted by the methodology of the U.S. Geological Survey balance against these informational issues? In a larger sense, we need to investigate the benefits of objective data analysis and integration as compared to employing the geologist to analyze and integrate basic geodata. To the extent that the various kinds of geodata provide information which is scale dependent or which interrelates in complex fashions, and to the extent that an experienced geologist understands these complexities, the use of the geologist as an active participant in an appraisal system seems desirable. However, if the ability of the geologist in these regards is quite limited, the undesirable features of subjectivity may outweigh the small benefits that derive from his or her analysis and integration of geodata. At present, we are just recognizing relevant questions. Improved appraisals and appraisal methodologies will require many iterations on theory, methodology and data.

The next section provides a demonstration of approach A (a system within which the geologist is an active component) on the estimation of uranium endowment of the San Juan Basin, and an experiment on the effect of methodology (implicit compared with explicit) on estimates of uranium endowment.

An Experiment and Case Study of Implicit versus Explicit Endowment Estimation

Perspectives of Experiment. This study can be viewed as an experiment on the effect of methodology on subjective estimates of endowment; more specifically, it examines estimates of uranium endowment of the San Juan Basin of New Mexico made by four geologists, each using two methods of estimation: 1) implicit and 2) an appraisal system which employs the geologist's formalized geoscience. The latter method was referred to in a previous section as the Arizona system. This system requires the geologist to integrate and analyze all geodata as a means of providing probability statements to the computerized decision model about the states of the processes and geological conditions that are identified as decision variables within the system.

Each of four expert geologists was asked to examine the stratigraphic column for the San Juan Basin and to identify those lithologic or formational units that they would group together for the purpose of uranium endowment appraisal. (Initially, five geologists participated in the study, but one of these did not satisfactorily complete the calibration of his model; consequently, the estimates of only four geologists were analyzed.) Table III shows the groupings, referred to as stratigraphic units, made by one of the geologists (code-name, Curly) who participated in the demonstration.

Subsequent to identifying such stratigraphic units, the geologists were asked to partition the geographic distribution of each stratigraphic unit into geographic subdivision (partitions) which are relatively homogeneous with respect to the earth processes and geologic conditions that influence uranium endowment. The second column of Table III shows the number of partitions delineated by one of the geologists for his stratigraphic units. Thus, this geologist made 50 (total number of partitions) appraisals of U_3O_8 endowment by each methodology. Figure 8 shows the geographic locations of partitions for the Westwater Canyon member of the Morrison Formation.

Subsequent to the identification of stratigraphic units and their partitions, each of the four geologists estimated the uranium endowment of each of the partitions by two main methods: implicit and appraisal system. As explained previously, implicit estimation of uranium endowment for a partition consisted of providing selected percentiles of endowment, given the partition's geology. The lognormal distribution which best fit these percentiles is referred to as an Implicit 1 estimate for the partition. Subsequently, the geologist was shown the statistics of the fitted lognormal distribution and allowed to modify the initial percentiles. A lognormal distribution fitted to the revised percentiles is known as an Implicit 2 estimate. Subsequent to estimation of endowment of all partitions by implicit analysis, the geologist was required to estimate uranium endowment using the appraisal system which he had previously constructed and calibrated and which had been computerized. Estimation of the uranium endowment using this system consisted of answering questions posed by the computer about states of the earth processes and geologic conditions in the partition of interest. Table I shows responses of the geologist who was code-named Curly to his decision model for a typical Westwater Canyon-Brushy Basin section. The appraisal system accepted these index numbers as input and pro-

Table III *Summary of typical resource assessment Open File reports published by Geological Survey of Canada*

1. Geological compilation map of assessed area (base map).
2. Mineral deposit/occurrence distribution map (coal, oil/gas in some cases).
3. Description, classification and listing of known mineral deposits/occurrences (computer printout format).
4. Capsule geological descriptions and interpretations of assessed area(s).
5. Extensive bibliography.
6. Mineral potential ratings derived by experienced economic geologists.
7. Text discussions of rationales and method(s) used in deriving assessment ratings.

duced a probability distribution of U_3O_8 as output. This probability distribution is referred to as a System estimate. Thus, for a given geologist, this study produced three estimates of U_3O_8 endowment for each of his partitions. Mathematical techniques were used to compute from partition distributions a probability distribution for the uranium endowment of the entire San Juan Basin averaged across geologists.

Results of Experiment. Figure 9 shows the average composite distribution for the Basin by Implicit 1, Implicit 2, and System methods, plus a fourth one, the NURE 1980 estimate made by the U.S. Department of Energy (1980). In terms of decomposition and control on hedging, these four methodologies are ranked from least to greatest as follows: Implicit 2, Implicit 1, NURE (1980) and System. This figure suggests that the greater the opportunity for hedging and the use of heuristics, the smaller is the estimate of expected (mean or average) U_3O_8 endowment and the narrower is the 90 percent confidence range.

Earlier in this paper the use of heuristics for the subjective estimation of the state of an uncertain event, particularly a compound event, was introduced. Furthermore, the general observation of psychometricians is that the use of these heuristics results in biases (Tversky and Kahneman, 1972, 1974; Slovic, 1972) and a considerable understatement of the variance of the event – subjective distributions have been observed to exclude 40% to 50% of the states described by the true distribution. In this study we do not have a statement of "ground truth", i.e., the true amount of U_3O_8 endowment for the San Juan Basin; therefore, we cannot make unequivocal judgements as to which methodology produces the most accurate probability distribution. The strongest judgement that can be made is that the 90% confidence ranges for Implicit 1, Implicit 2 and System estimates compare to each other as experimental results and theory of subjective assessments suggest they should. That is, estimation of the compound event by estimating the states of its components and subsequently recomposing endowment from its components produces a much broader distribution than the one obtained by unconstrained subjective processes.

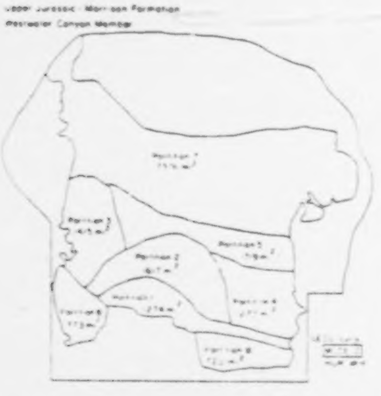


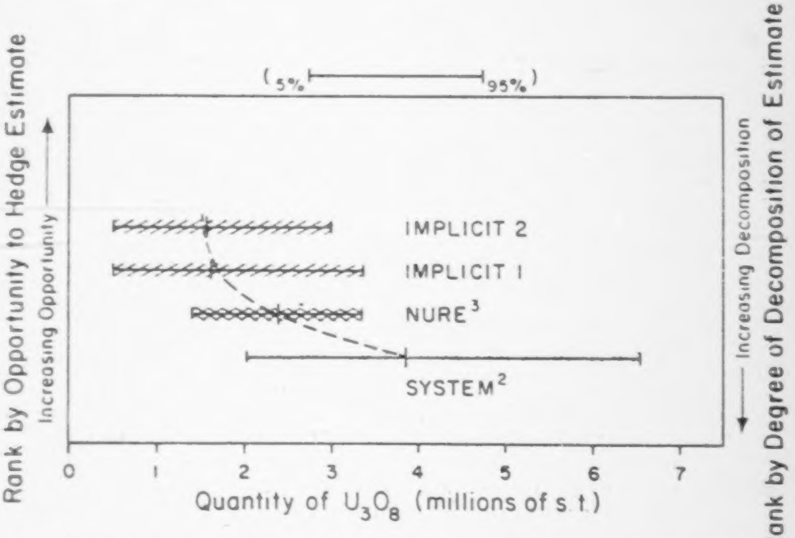
Figure 8 *Partitions made by geologist Curly of the Westwater Canyon Member of the Morrison Formation (Harris and Carrigan, 1980).*

An *a priori* ranking of methods by the degree to which they decompose the estimation process, and hence mitigate narrowness of distribution and discourage hedging is also the correct ranking by size of expected endowment produced by these methods. With exception to the NURE estimates, this a priori ranking is also the correct one for breadth of the 90% confidence range. The system-estimated distributions generally have both the largest expected value and the largest 90% confidence range. Since this methodology employs great decomposition and many decision aids, these results agree well with *a priori* expectations based upon findings and theories of psychometricians regarding the subjective assessment of an uncertain event.

Basically, this study found that use by the geologist of explicitly stated geoscience to evaluate the geology of the San Juan Basin indicates a greater endowment of U_3O_8 than has previously been estimated. However, this study also found that there exists much greater uncertainty about the magnitude of the U_3O_8 endowment of this region than has previously been expressed.

An Improved Estimation by Approach A

In this section, I wish to limit the subject of predictive metallogeny to the circumstances identified in the introduction to this paper, namely to a region for which geodata are available but which has been only lightly explored and within which there are at most a few known orebodies, although there may be a number of recognized mineral occurrences. Estimation of mineral endowment for such a region is at best a difficult task because of the lack of sufficient development of mineral resources to allow the formal investigation of relationships of geological features to magnitude of mineral occurrence. The "scale" dimension of prediction is very difficult to deal with for such regions. Of course, there are no easy and satisfying solutions to the problem of prediction for this circumstance, and there are only two basic avenues to prediction:



[1] Initial endowment = Mineral inventory + Cumulative production + Potential

[2] Average of estimates by four geologists, each using his own appraisal system

[3] For the calculation of Initial Endowment, the assumption was made that the mineral inventory for the Colorado Plateau region is the mineral inventory of the San Juan Basin

Figure 9 *Graphic comparison of estimates of initial U_3O_8 endowment of the San Juan Basin—expected values and 90% confidence ranges (Harris and Carrigan, 1980).*

1. the use of one or more basic relations of element concentration and geologic processes
2. the use of an empirical relationship, such as the relationship of quantity of endowment to geology, observed from previous experience on other regions.

Crustal abundance and geochemical cycles represent attempts to take the first of these avenues; however, these have not included geologic conditions or processes. Since geology varies considerably, at least across small regions, a basic relationship which accommodates such variation clearly would be ideal. My experience with geologists has been that they have great difficulty in approaching prediction in this way. The geologist's geoscience does not prepare him or her for this task. At least at the present, some empirical relationship or model seems to be needed. Perhaps some of the principles of predictive metallogeny cited in this conference by Dr. Rundquist, e.g., Curie-Shafranovsky symmetry and spatial and time similarities, may be useful in this regard.

In the remainder of this section, I wish to explore the second of these avenues, the use of an empirical relationship of geology to endowment observed on other regions. Taking this avenue requires that the empirical relationship be general enough that differences in observed geology of the region being evaluated and of the control regions do not challenge the credibility of the prediction, or that the relationship be dynamic in that it contains as explanatory (decision) variables those geologic conditions which account for regional variations in geology and endowment.

The approach that is described in the remainder of this section employs geologic decision analysis combined with statistical analysis. Simply stated, this approach would preserve the richness and flexibility – and other benefits, mentioned in previous sections – that result from formalizing geoscience, using earth processes as much as possible. But, the geologist would not be asked to link process states or geologic conditions to magnitudes of mineral endowment, as was done in the Arizona system and the experiment on the San Juan Basin of New Mexico. Instead, this linkage would be made by a statistical relationship between known endowment and the probabilities for major process states computed by the geologic decision model for control areas. As is explained below, this linkage requires additional information, information on exploration intensity or thoroughness of search for each control area. In fact, this information is as important to this approach as are geodata.

Before explaining the approach to linking the geologic model to endowment, a comment on motivation is in order. The previous sections identified advantages of formalizing geoscience, linking the resulting decision model to endowment in an appraisal system and using this system for the estimation of endowment. These benefits included reduction of heuristic biases, control on hedging, a documented procedure and educational benefits of modelling.

The experiment on the San Juan Basin suggested that uncertainty about uranium endowment is much greater than is indicated by implicit estimates. This experiment revealed that the singularly most difficult and uncertain dimension of modelling is the linkage of the major processes or geological conditions of the decision model to magnitude of endowment. Undoubtedly, this uncertainty is a major contributor to the greater variance in the system distributions. To the extent that the objective of an appraisal is to express the true uncertainty in the minds of the appraisers, forcing the geologist to deal with this uncertainty is best procedure. Avoiding it, as is done in the implicit methodology, does not remove the uncertainty; it only ignores and suppresses it.

There is, however, another perspective to be considered: the variability of endowment in nature versus uncertainty in the mind of the geologist. Suppose that geologists had perfect knowledge of the relations between earth process states and magnitude of endowment. But, suppose that for a given region they had no knowledge of the states of some of the processes. If they were able to examine a universe of regions which had the same circumstances of known and unknown processes, they would observe a distribution of endowments. Consequently, even given their perfect knowledge of the abbreviated relations, the effect of some processes being unknown is a probability distribution for the unknown endowment for any region under consideration. It is this distribution – a distribution of endowment in nature – which is desired when estimating mineral endowment. Geology and the geologist are a means of reaching this objective; furthermore, formalizing geoscience into a decision model is a rational approach. However, to the extent that geologists are very uncertain of the relationship of earth processes to magnitude of mineral endowment, their subjective distribution, if accurately measured, will reflect much greater variation in the magnitude of endowment for a region than is present in nature. If this uncertainty were great, the subjective distribution would approach a rectangular distribution with a wide range of possible states of mineral endowment, even when endowment in nature is normal or lognormally distributed. Thus, if our objective is to have a good estimate of the distribution of uranium endowment in nature, we may not be satisfied with a rectangular distribution when that distribution shape is believed to express a high level of ignorance. On the other hand, the subjective distribution may be preferred in an exploration model, because the uncertainty of the geologist is a real component of exploration performance and cost.

Let us assume here that the objective of predictive metallogeny is to describe variation in nature. Then the difficulty experienced by the geologists in the San Juan Basin demonstration in linking mineral endowment to the geologic decision model raises a question about the impact of ignorance and motivates the desire for an alternative approach, one which would make this linkage by statistically analyzing known states of nature and the states (or probabilities for the states) of the earth processes and geologic conditions of the geologic decision model on well known (control) areas. If achievable, such a linkage may provide a better estimate of variability in nature. It is with this motivation that the follwing approach is described.

While linking the decision model to endowment by the quantitative analysis of data is immediately appealing in concept, implementation of such a linkage would require 1) endowment data, such as either the number of deposits or the fraction of the partition that is mineralized and 2) data on the states of the earth processes. We have neither of these kinds of data. For one thing, resource data reflect only what has been discovered, not what is there. Even so, we may be able to use such data to achieve our objective. Consider this proposition: the fraction of an area (or number of deposits per unit of area) that is presently known to be mineralized is a function of geologic favourability of the area and the intensity to which this area has been explored. Let us formalize this by representing the fraction by f, geologic favourability by the 27 probabilities, $P_1, \ldots, P_{27}$, one for each combination of major process states, and exploration by v:

$$f = (\alpha_1 P_1 + \alpha_2 P_2 + \ldots + \alpha_{27} P_{27})(1 - e^{-\alpha_0 v}) \qquad (1)$$

Thus, if the coefficients, $\alpha_0, \alpha_1, \ldots, \alpha_{27}$, were known, given the 27 probabilities and the amount of exploration, the equation would yield an estimate of the fraction of the area known to be mineralized. Of course, our objective is not the fraction known at present but the actual fraction. Even so, if the coefficients were known, by setting v to infinity, we could obtain an estimate of the actual fraction. The advantage of this approach is that it does not require data on the actual f, only on the presently measurable fraction. Of course, to estimate this equation, we must also have data on the 27 probabilities and on the amount of exploration, *v*. The remainder of this section "walks through" how this approach might be implemented.

Suppose that the geologic decision model were complete, meaning that it would have been calibrated satisfactorily: the probabilities computed by the system for states of the three major processes, given the probabilities for the states of the minor processes, for each reference condition would be satisfactory to the team designing the system. Suppose further that states of the major processes were not yet linked to endowment.

Suppose also that other, independent efforts had recorded for each partition *v*, the amount of exploration per square mile conducted in that partition, or some other description of exploration maturity, such as drilling density or conditional probability for existence of a target. Suppose that for every partition, the presently known fraction, *f*, were recorded. Finally, suppose that the geologists had described the geology of each partition probabilistically, just as was done in the study by Harris and Carrigan (1980). The input data to the geologic decision model – probabilities for the states of the minor processes or geologic conditions – could be processed by the geologic decision model. The output of the decision model for each partition would be probabilities for each of the three states of each of the three major processes. Accounting for all combinations of major process states, there would be 27 probabilities for each partition, one probability for each combination.

Let us summarize what has been postulated. Consider Figure 10, which is a hypothetical map of partitions of some stratigraphic unit. Only those partitions which have received significant exploration are of interest at the moment. For each of these partitions, there are three kinds of information:

v_i = exploration effort in the i^{th} partition.

f_i = fraction of the i^{th} partition known at this time to be underlain by uranium mineralization (alternatively, this measure, f_i could be number of known deposits per unit of area).

$P_{1i}, \ldots, P_{27i}$ – probabilities for each of the 27 combinations of processes states for the i^{th} partition.

V_i and f_i are measured data, but $P_{1i}, \ldots, P_{27i}$ are computed by the decision model. Suppose that this procedure were repeated for each of the geologists's stratigraphic units and that a table of these data over all units were prepared, such as Table IV. The data of Table IV could be analyzed by statistical and computer methods, e.g., iterative or non-linear regression analysis, to give estimates of $\alpha_0, \alpha_1, \ldots, \alpha_m$, where $m < 27$:

$$\hat{f} = (\hat{\alpha}_1 P_1 + \ldots + \hat{\alpha}_m P_m)(1 - e^{-\hat{\alpha}_0 v}) \quad (2)$$

This equation provides an estimate of the fraction of the area that is presently known to be mineralized (contains endowment).

Since the sum of 27 probabilities is 1.0, only 26 probabilities are needed to convey the probability information. Furthermore, while conceptually only 26 probabilities are required to convey full information, an analysis may find that with respect to the data analyzed on endowment and exploration, less than 26 probabilities convey statistically meaningful information. This is a likely result, since very little, if any, endowment may be present when the states of all major processes are poor. Consequently, P_m, the last probability in the equation, may be the sum of several of the probabilities for the least favourable combinations of process states:

$$P_m = \sum_{i=m}^{28} P_i \quad (3)$$

Thus, the equation which results from the analysis of data may require fewer coefficients than indicated conceptually:

$$\hat{f} = (\hat{\alpha}_1 P_1 + \ldots + \hat{\alpha}_{m-1} P_{m-1} + \hat{\alpha}_m \sum_{i=m}^{28} P_i)(1 - e^{-\hat{\alpha}_0 v}) \quad (4)$$

For example, it is conceivable that statistical analysis could indicate that as few as 10 probabilities are required ($m = 10$), meaning that probabilities P_{10} through P_{28} are summed and treated as one probability.

To see how Equation 2 would be used, imagine that by implementing the decision model we have a set of 27 probabilities for each of the partitions, those explored and unexplored. Suppose that for each partition the intensity of exploration were specified to be infinity. Since $1 - e^{-\hat{\alpha}_0 v}$ evaluates to 1.0 when $v = \infty$, the above relationship is reduced to $\hat{f} = \hat{\alpha}_1 P_1 + \ldots + \hat{\alpha}_m \sum_{i=m}^{28} P_i$. Thus, evaluation of this equation at $v = \infty$ and with the probabilities computed by the decision model for a partition would provide an estimate of the expected actual fraction of the partition that contains endowment.

Regression analysis also provides *S*, the standard error of the estimate, $\hat{f}$. Thus, by employing the assumptions of the regression model and the statistics $\hat{f}$ and S, we would be able to describe a probability distribution for *f* for each partition, given $P_1, \ldots, P_m$ and $v = \infty$. In this way, it may be possible to avoid the subjective linkage of the decision model to endowment. Of course, implementation requires the measurements of currently known *f* and of *v* for each partition that has received any significant amount of exploration. Furthermore, implementation of this approach for appraisal would require the description of a histogram or a probability density for the amount of U_3O_8 in a mineralized cell (subdivision of a partition). This would be an input to the synthesis program. While such data have not routinely been gathered, they could be, given a concerted effort by knowledgeable persons to measure or estimate them.

In summary, by using only the geologic decision model component of the appraisal system, data on the states of the major earth processes in each partition can be generated. If for each explored partition these data are augmented with measurements on exploration and the fraction of the

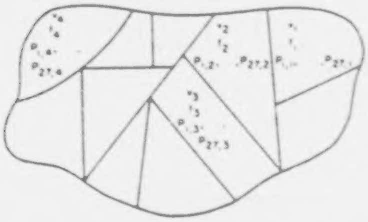


Figure 9 *Graphic comparison of estimates of initial U_3O_8 endowment of the San Juan Basin—expected values and 90% confidence ranges (Harris and Carrigan, 1980)*

Table IV *Data Tableau*

Case	Exploration (v)	Fraction (f)	Process Probabilities (P_1 P_2, . . . , P_{27})
1	v_1	f_1	$P_{1,1}$ $P_{2,1}$, . . . , $P_{27,1}$
2	v_2	f_2	$P_{1,2}$ $P_{2,2}$, . . . , $P_{27,2}$
		⋮	
n	v_n	f_n	$P_{1,n}$ $P_{2,n}$, . . . , $P_{27,n}$

Source: Harris and Carrigan, 1980.

partition currently known to be mineralized, the earth process of the geologic decision model could be linked to endowment by a statistical relationship determined by the quantitative analysis of these data. This relationship could replace the subjective conditional probability distributions for *f* or number of deposits that the system currently employs.

There is another benefit of this linkage approach when the objective is to average the system estimates made by two or more geologists: it would provide a means for weighting the estimates by the geologists. In the demonstration of the system on the San Juan Basin, a simple (unweighted) average was computed because there was no objective way of weighting the responses of the geologists. But, if the statistical analysis described in this section were made separately for each geologist, using the probabilities computed by his or her system but using the same data on exploration and *f*, a measure of the fraction of variance in the known *f* that is explained by decision model probabilities and exploration effort could be computed for each geologist. This fraction of explained variance could be employed as a weight for the computation of a weighted average endowment distribution. Simply stated, such a weighting scheme would weight preferentially the estimates of those geologists whose model's estimates were most compatible with known endowment.

In summary, I offer the suggestion that for frontier (lightly explored) regions, a useful initial contribution to estimation is an estimate that is based upon formalized geoscience and a linkage of this geoscience to endowment by statistical analysis of known endowment and probabilities for the major processes states computed from the decision model. Application of this approach requires a geologic model that is sufficiently general and dynamic that it accommodates a wide variety of geologic environments. Predicating the geologic model upon earth processes instead of upon recognition criteria may facilitate the required generality and dynamics. A methodology like this would preserve the flexibility and richness of geoscience, maintain the geologist as an integrator and analyzer of geodata and retain statistical credibility of estimates.

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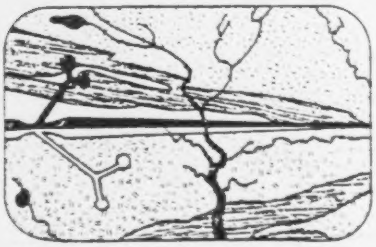

4. Predictive Metallogeny: A Two-Edged Sword

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Introduction

The ability to predict the location of undiscovered mineral deposits and, further, to have some inkling of their type, size and grade is the ultimate aspiration of the economic geologist. Like many ultimate goals, it is at present beyond our reach. It is vitally important that this should be recognized at the outset of any discussion of predictive metallogeny. By pretending otherwise we not only delude ourselves, but can seriously mislead non-geologists, such as politicians, economic planners and the owners of mineral rights who depend on our council for their guidance.

In discussing predictive metallogeny my viewpoint is that of the profit-motivated private sector of the Canadian mineral exploration industry. In addition to Canadian experience, I will draw upon experience in the United States and other parts of the world, experience gained over a period of twenty years of mineral search. During that time, I have been fortunate enough to have been associated, directly or indirectly, with two highly successful applications of predictive metallogeny, and with several other "technical successes" in which mineral deposits were found which were not immediately mineable. Please note the distinction between "successful" and "technically successful" used here, as the distinction is the key to the viewpoint of the mining company. According to this viewpoint, it is of little value to find mineral resources unless they can be exploited profitably within a reasonable time frame, usually twenty years or less.

Mining Company Exploration Procedures

There is little unanimity or conformity in the approaches of various mining companies to mineral exploration. Nonetheless, companies tend to fall into certain broad categories. For example, companies may be *active* or *passive*. Active companies initiate exploration, passive ones allow entrepreneurs or other companies to bring proposals and properties to them. Among the active companies, some are oriented towards the *acquisition* of prospects at various stages of development, whereas others pursue a *grassroots* approach, developing their own concepts and pursuing them in the hope of finding previously unrecognized deposits. Most of the more successful companies employ a mix of the acquisition and grassroots approaches. Some companies direct their efforts towards a single commodity or a single geographic area, others seek a wide range of targets and pursue their objectives throughout the politically and economically favourable parts of the world.

Whatever the approach, the driving force is the desire to make a profit. Exploration is a tool to achieve corporate objectives. When the objectives have been attained, or when it is clearly demonstrated that they cannot be attained economically, exploration stops. Much of what I have just said is elementary and self-evident, but it bears repeating in the hope of avoiding the misundertandings that can arise between the government, academic and industrial factions of our economic geology community. For example, in his letter confirming my invitation to sit on this panel, Atholl Sutherland Brown, speaking for the Committee of Provincial Geologists, identified the subject of predictive metallogeny as one needing more open discussion and more systematic and innovative approaches. Granted. However, he went on to say "We believe that there is a large amount of *ad hocery* in the business of designing exploration programs". My dictionary defines *ad hoc* as "arranged for a purpose", or "special". My point is that an exploration program mounted by a private company will always be *ad hoc*, in that it is designed to achieve a specific, profit-motivated corporate purpose, usually within a restricted time-and-expenditure frame. Accepting this fact, one is led to conclude that long-range, systematic studies aimed at elucidating the origin and distribution of mineral deposits are outside the normal realm of the mining companies, and clearly become the responsibility of the government agencies and other research organizations which have the consistency of policy and funding to carry them out, and the obligation to publish their findings. However, to be most effective, the groups charged with carrying out metallogenic studies must maintain close contact with the exploration industry, which is the crucible within which long experience, daily exposure to new data and the motivation of profit are fused to form new exploration concepts and techniques.

Two Success Stories

I would like to describe two successful exploration programs which represent ideal applications of predictive metallogeny to the search for ore. They are Amax's long campaign which culminated in the discovery of the Henderson, Crested Butte and other molybdenum deposits, and Texasgulf's Canadian Shield program which led to the discovery of the Kidd Creek orebody.

The Amax example, seen from the perspective of hindsight, was a classic exploration exercise. The description which follows is very general and is derived from my own experience as a brief participant in the program some twenty years ago.

At some time in the mid-fifties, the American Metal Climax Company, then, as now, the world's predominant producer of molybdenum, decided that the market outlook for their product required a major effort to locate new reserves for future exploitation. A team of experienced geologists was charged with compiling data on all known molybdenum deposits. From this compilation arose several important conclusions. One of these conclusions was that only the Climax-type molybdenum deposit was worth looking for. This conclusion eliminated the pegmatite, skarn and other deposit types from consideration, and enabled the company to focus its attention in one direction.

From careful study of deposits of the Climax type, a set of parameters was derived, including the following:

1. the gross tectonic-petrologic environment of the desired deposits
2. the age and composition of the associated plutons
3. the specific localizing structural environment
4. the nature of the alteration imposed upon the host rocks

In today's parlance, they developed a "conceptual model", although that term was not in use at the time.

Armed with the model, amply funded and backed up by corporate persistence, Amax geologists pursued their objective from Alaska to southern Chile, with a side trip to Greenland. In the course of the program the original exploration parameters were modified and new exploration techniques were developed, particularly in geochemistry. Over the years, geologists came and went, thus gradually spreading the newly developed technology throughout the industry.

When success finally came, it was in Amax's own backyard, the Colorado Mineral belt. Roughly ten years had passed since the inception of the program before the first significant drill intersection was obtained from the Henderson orebody, and a further ten years passed before Crested Butte was found. These two magnificent discoveries, each with immense reserves of high-grade ore, are a fitting reward for the high-risk, long-term investment of corporate resources.

My second example also was stimulated by a corporate policy. Prior to 1950, Texasgulf had been essentially a sulphur company, with little activity outside the gulf coast of the United States. Early attempts to diversify were largely sporadic and poorly funded. They did, however, lead to the accumulation of a body of imaginative people, as well as data and experience concerning massive sulphide deposits. From these ingredients, a concept arose concerning the genetic and spatial relationships between rhyolitic volcanic rocks and the concordant, base metal-bearing massive sulphide deposits. In 1957, the decision was made to apply this concept to that part of the Canadian Precambrian Shield which lies between Chibougamau and Flin Flon. The implementation of the project was facilitated by two events: one was a strong corporate drive towards diversification, the other was the recent development of the airborne electromagnetic method. The first factor ensured the support of head office and adequate funding; the second provided a rapid and effective means of evaluating the large number of prospective environments identified by geological compilation and field work.

In November of 1963 the program culminated in the discovery of the Kidd Creek orebody north of Timmins, Ontario.

These two successful exploration programs or, more specifically, the proposals which were put forward at the start of each program, were exercises in predictive metallogeny. In each case all available data were compiled before field work was undertaken, a conceptual model was developed and selected areas were investigated in the field to identify prospective environments. Some other important features of the process were as follows:

1. In developing a conceptual model to guide the search, full advantage was taken of the backlog of experience and data available because of the sponsoring company's earlier involvement in mining and exploration.
2. From the outset, an economic model was also in place, in that the target was an orebody, which must be mineable under a specific set of parameters which prevailed at a given time for an individual company.
3. The studies which led to the programs were *qualitative*, rather than *quantitative*. The sponsoring companies and their staff who developed the programs knew better than to try to quantify the expected results.
4. The geographic scope of the projects was dictated by geology alone, not by any political boundaries.
5. The participants understood the risk involved in their investment; they knew that there was no assurance of success, and they had the resources to carry the programs to completion.

It is instructive to compare the foregoing characteristics of the two successful company exploration programs with the characteristics of many of the exercises in predictive metallogeny carried out by government or academic organizations in recent years.

1. *Motivation*. Most predictive metallogeny exercises, or resource appraisals, are carried out at the instigation of political or economic planners, who have little understanding of the capabilities or the limitations of economic geology.
2. *Staff*. The individuals who do the work, although they may be skilled scientists, commonly have little background in the applied aspects of geology.
3. *Data base*. Many evaluations are based on published geological maps which have been made by geologists who are relatively uninterested in mineral deposits and who are not trained to recognize the peripheral indications of hidden mineral deposits. In most Canadian provinces, the compilers of metallogenic maps commonly pay little attention to the assessment files with their wealth of data of economic mineral occurrences.
4. *Misuse of data*. Many attempts are made to produce quantitative data, usually on the basis of questionable statistical assumptions, or the equally dubious concensus of a group of "experts" on the region involved or the deposit type sought. The "quantitative" data from such studies, taken out of context and used by economic planners or "simplified" by the media, can be very misleading. Bad economic planning and misuse of public funds can result from the improper use of so-called quantitative resource appraisals.

Conclusions

The past 20 years has been a period of growth in the use of various forms of predictive natural resource assessment in North America. Controversy has surrounded many of the applications of the technique, usually being sparked by violent differences of opinion between private industry and the agencies responsible for the studies. An example which caused public consternation was the Club of Rome's ridiculous misinterpretation of geological data to derive a doom and gloom scenario for the world's near-term supply of metals. Another instance, which should have revealed to all the weakness of our predictive skills, is the continuing controversy over the extent of hydrocarbon resources. Still another massive difference of opinion arose in the United States about a year ago, when very negative federal government findings on domestic phosphate rock resources were totally rejected by spokesmen for the mining industry. The federal study had assumed that consumption would accelerate, but that there would be no technological advances to permit the increasing of reserves by material not mineable at present. No justification was given for the obviously false assumption that exploration, mining and processing technology, which have improved fairly steadily over the past twenty or thirty years, would suddenly become stagnant.

The fundamental conflict between the academic approach to predictive metallogeny and that of the exploration geologist is displayed dramatically in a brief but spirited exchange of Letters to the Editor generated by DeVerle P. Harris' paper entitled *A subjective probability appraisal of metal endowment of Northern Sonora, Mexico* (1973). To attempt here a summary of the paper and the discussion it provoked is not feasible. Suffice it to say that the author's work "yielded an expectation of approximately 2600 tons of metal per square mile" in this study area, and led him to estimate that roughly one-quarter of this could be found and mined profitably under the economic conditions of the time. The paper was written in 1973; in hindsight, one wonders what part of the expected metal would have been mineable three years later, in 1976, under the drastically different economic conditions that prevailed then. Not surprisingly, Sobel, an experienced economic geologist with a fair amount of field time in Sonora, vigorously and not too politely disputed both Harris' methods and his findings. He offered his own conclusion as to how the study could be summed up: "Ten experienced geologists feel that a good chance exists to find new mineral deposits in Sonora; the choice sites to explore are close to known deposits." The correspondence ends with the author's reply to the criticism, in which he defends his position with the interesting statement "it matters not that the task is a dirty one, that the phenomenon of mineral occurrence is not completely understood, or that information is often too meagre to give high or even moderate reliability to estimates. Mineral resources appraisals often must be made in spite of these obstacles". Accepting that there is a general and increasing need for mineral resource appraisals is not difficult; accepting that they must be quantitative is more difficult, in view of the very problems expressed by Harris. The weaknesses in the basic data and assumptions used can be expressed properly when the communication is in the form of a scientific paper exchanged between consenting adult earth scientists. The problem arises when the quantitative conclusions are taken out of context by members of the communications media, politicians or bureaucrats, and unknowingly used in an improper manner. Such misuse, as noted earlier, can lead to unwise expenditure of public or private funds, unfair taxation and unrealistic mining laws.

To close on a more positive note, a few words about the various approaches to — predictive metallogeny. The one which currently appeals most to me is the type presented in recent Geological Survey of Canada resource assessment studies for various parts of northern Canada. As described in a recent paper by Findlay and Sangster (delivered at the Annual Meeting, CIMM, Quebec City, 1982), the reports are subjective geological assessments that present areas or packages of rocks "in terms of their perceived potential to contain undiscovered mineral deposits". The ratings are essentially qualitative, and are derived by matching the geological characteristics of selected terrains with the diagnostic features of the conceptual models of various mineral deposits. The appraisals are documented abundantly so that the user can see clearly how the rating was determined. Findlay and Sangster note that the asessments are "broadly equivalent to the initial compilation stage of many exploration programs", which probably explains why they are so acceptable to me!

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Harris, DeVerle P., 1973, A subjective probability appraisal of metal endowment of Northern Sonora, Mexico: Economic Geology, v. 68, p. 222-242. See also p. 1344-1346 of same volume, including discussion by Harvey L. Sobel and author's reply.

Invited Discussions

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I will try to present the view of an exploration geologist about predictive metallogeny, what in the old days we used to call "having a nose for ore".

The panellists have outlined various methods: empirical, qualitative methods using subjective judgement with or without mathematical computations, quantitative methods with objective judgement. Predictions are done by a variety of people, ranging from those closest to the scene, i.e., field geologists, to exploration managers, pure scientists, mathematicians and even astrologers. Predictions are commonly based on an analysis of a control area and an effort to apply it to the area that is being assessed. By analyzing the total geological picture, ore deposit models and frequency distributions, one sets probabilities of occurrence in this and that area.

To me, predictive metallogeny has two major levels. When it is applied to a mature mining district that has a good data base obviously the events are more predictable and you have more confidence. It is like finding blueberries in a blueberry patch: you know you're in a patch and even can tell after some time what size, quality and shape the berries will have. The real rub comes when you go into an unknown area where there is a poor data base and events are less predictable. But this is where predictive metallogeny really has to reach, this is where it is most important to be able to answer the question, "are we in elephant country?". And the second level is the "exploration surprise factor". Quite often in the field when you least expect it you find yourself on candid camera. No one said there was going to be ore there, but by God it's there! Anyway, reviewing the past 30 years of Precambrian discoveries, I can think of 10 or 12 camps, Manitouwadge, Snow Lake, Thompson, Elliot Lake, Kidd Creek, Detour Lake, Athabasca Basin—I won't name them all—about which who cannot say that, despite all the data present at the time, they were surprised when these discoveries were made: and made by others!

Let's take Case 1, the uneven endowment factor. Timmins: a pre-1964 major gold district, over a quarter of Canadian Precambrian gold production, 50 years of history, 2 or 3 minor copper-zinc deposits. Now who in all honesty would have predicted to his exploration management that he needed certain funds because he knew there was going to be a world-class copper-zinc-silver deposit just 10 miles out of town? The Kidd Creek deposit in itself is equal to all the production of the the gold mines in the Timmins area.

This fantastic deposit is 25 times larger than the average Precambrian deposit. It is even three times larger than the largest known Precambrian deposit. Mathematically, you cannot predict an event like that because of its uneven endowment factor and you have no control over it. Now you can draw contours around it mathematically and as you move in closer to the bull's eye you come in second, because you'd have homed in on Kamkotia which is about 6 million tons. Eighteen years have passed since that discovery and nothing of any consequence in massive sulphides has been found there. Who will care to predict the next discovery— its size, grade and location?

Case number 2 exemplifies the surprise factor— geological surprise. The Athabasca basin, pre-1968, consisted in essence of the Beaverlodge deposit, a classic vein model type deposit with a 25-year history. Despite the uranium exploration going on around Uranium City, the unconformity model was developed, with Cluff Lake, Key Lake, etc. Unknown to the geologists or the mathematicians or anyone else, there happened to have been a change of ore deposit habitat. The ore locale changed. The ore was in the area but it wasn't in the veins anymore. So how can you predict that quantitatively?

From the viewpoint of exploration, I am inclined towards the use of a qualitative method, subjective approach and, to coin a phrase, "simple intuitive method", and to review areas in terms of their having or not having a tendency toward containing either a high, medium or low probability of discovery of the type you are looking for. When you are working in a mature district where there is abundant data you can afford the luxury of a semi-quantitative or perhaps even a quantitative approach. In a very restricted area, where perhaps 20 discoveries have been made over 30-50 years, and the geometry, the ore deposit size, shape and grade and the frequency distribution are known, then you can perhaps afford the luxury of calculating to one decimal place, but I wouldn't go beyond that.

Also, I am inclined toward using predictions expressed in relative terms and not necessarily in absolute terms. That is where the trouble begins, when you become absolute.

In closing, I believe that predictive metallogeny is really an art and not necessarily a science. The artistic aspect is that of predicting with reasonale accuracy from minimum data and in minimum time. And to quote Niels Bohr, "Prediction is a very difficult business, gentlemen, especially when dealing with the future".

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Julian Boldy and I agreed that we'll look at the subject today from opposite ends of the country. I'm looking at it through the eyes of a westerner and he as someone who has worked primarily in eastern Canada. I think two things are clear from what we have heard this afternoon. First, George Mannard doesn't agree with DeVerle and second, we are all of us still confused about what predictive metallogeny is, though I think we're starting to zero in on the problem.

My first-hand experience with resource estimation started about 15 years ago when Barry and Freyman applied the Delphi technique that Don Sangster referred to earlier and which was somewhat like the one DeVerle talked about. Barry and Freyman toured Canada, primarily in the west, and asked a number of knowledgeable explorationists who had worked in the Yukon and British Columbia to try to estimate mineral potential for a large number of small cells. The results were synthesized and appear to have been remarkably perceptive. I am sure that none of us who took part in that project 15 years ago would have guessed that it would turn out so well.

My second involvement with resource estimation was through a paper that was published in the CIM Bulletin (v. 85, April 1982) on base metal deposits that we refer to as the sedex type, a contraction of sedimentary exhalative. Julian Boldy, when he was chairman of the CIM Geology Division, had asked us to write a summary paper on the deposit type and we did not start out with a mineral appraisal in mind, but it was something in which we became involved while we were writing the paper because we thought that it fleshed out the descriptions and we wished to cover all aspects, and not just the mineralogy and lithology. Furthermore, it would also give some idea of whether or not it was an important resource. When you look at the paper you'll see that it's a different approach used to try to estimate resources and reserves, and it is patterned more on the lines used in the pertroleum industry to estimate quantities of oil and gas.

I think the title "Predictive Metallogeny" is perhaps an unfortunate choice because it means different things to different people depending on point of view. I think George Mannard and I would agree that it's a modern term to describe what we've always thought of as exploration planning. It's obviously being used today to talk about mineral appraisal. Those are two different things; they overlap to some degree but are certainly not the same and they are leading us in different directions. To me, it means the use of metallogenic studies to predict how and where to explore. If I understand Dr. Rundquist correctly, his approach in the USSR is probably closer to what we are doing in the industry in North America. That is not surprising, as his agency is involved in one of the steps of straight exploration.

I'd like to reiterate what George just said about the style that's being adopted by the GSC. The example displayed here by Dave Sinclair (1982) is also a very good way to go . I like it for the same reason that George does: it stops at the qualitatitive step and doesn't get onto thin ice by trying to become quantitative. Serious problems may arise when you try to quantify, because many of the deposit types are just too highly unpredictable. The sedex type about which we wrote the paper is more internally predictable. Once you find one, you have a pretty good idea where it will go and how large it will be, unless it is cut off by erosion or faulting. You know that you are looking at something that might be as small as 5 million tons and as large as 200 million tons and you have a pretty good idea of what the grade and the geometry are going to look like. But even some deposits that shouldn't be isolated or unique turn out to be notoriously so, e.g., Sullivan, for which no mate has been found in 75 years of search, even though common sense indicates that it should be part of a cluster. Another Cordilleran example is the Cantung deposit, the largest tungsten deposit in the Americas and perhaps in the westernworld. Common sense said that there had to be similar deposits in that part of the Cordillera because there were many areas with similar geological setting. Yet it was completely impossible to predict where they were going to be found. More have been discovered and there are probably even more to be found, but you would have been lucky to have been within 50-100 km of the location if you tried to predict just after Cantung was found. Even after the good geological mapping and the intense exploration, it's still almost impossible to determine where the next one is going to be.

In spite of the problems, there is no doubt in my mind that the process of preparing mineral appraisals is going to have to continue and improve. My involvement in the British Columbia and Yukon Chamber of Mines has given me valuable insight into just how seriously the mining industry is suffering from the lack of mineral appraisal preparations in the past. If the 1970s were notable for anything it was for the amount of high mineral potential land that was being either withdrawn from exploration or being considered for withdrawal. The process is going on unabated today, particularly in the west.

In addition to a late start, we've also had to face the problem that park proponents got a big jump on our scientists in capturing the initiative in preparing appraisals and also they were able to procure adequate funding in the days when there was a good amount of government money. Now they have budgets, even if restrained, that are large enough to prepare these things, while we do not. It's easier to count birds and fish and trees than it is to measure mineral potential, so it's even more incumbent upon us to begin this process and to work out the best ways of doing it.

I'd like to interject a word of caution before I close, and that is that it's often tempting for those who perform mineral appraisal to forget that their customers are the government and the general public; it's not the mining industry. It is very seldom that this type of appraisal is going to be used by the industry except by newcomers on the scene. Mineral appraisal is being done every day in every decent mineral exploration office, and believe it or not, some of the techniques being used are quite sophisticated and appear to work well. So I think it's important to direct your efforts and your money towards preparing the type of thing that your client, which is not the exploration industry, needs. If you want to do something for exploration I think you are far better off to put your efforts and money into a better understanding of the deposits models.

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Appendix D: Exploration Example #2

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PRECIOUS METAL EXPLORATION

by

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Exploration Session, Wednesday, September 30, 9:30 a.m.
Empire Room, Hilton Hotel

Presented at the 1981 American Mining Congress Mining Convention, Denver, Colorado, September 27-30

Homestake Mining Company is the largest gold producer in the United States and holds the largest known gold reserves in North America. Its position as the premiere domestic gold mining company has for years been based on the production from the Homestake Mine in Lead, South Dakota. More than 33 million ounces of gold have been extracted from this single location during the last 100 years of operation there. Homestake's position was strengthened last year with the discovery of another major gold deposit, the McLaughlin deposit, in a remote part of Napa County, California. That discovery was the result of an aggressive, new-technology exploration program, which the company began in 1978. Homestake now estimates that the McLaughlin deposit contains 3.2 million ounces of gold -- at least 20 million tons of ore with an average grade of .16 ounces of gold in each ton. Homestake expects the McLaughlin project to be in operation as a full-scale gold mine in 1984.

Homestake Mining has been an integral part of the history of gold mining in the United States. Its origins extend back more than 100 years when an expeditionary force led by General George Custer entered the Black Hills of South Dakota. Two miners, who were travelling with the soldiers, discovered gold at French Creek in 1876. A year later, two prospectors found an outcropping of gold ore in the same area. They dubbed the find a "homestake"--jargon for a claim rich enough to send the miners home in style. They later sold the claim to San Francisco financier George Hearst for $70,000. In 1877, Homestake Mining Company, founded to develop the claim, was listed on the New York Stock Exchange.

That mine continues to operate to this day, last year producing 267,000 ounces of gold worth approximately $100 million. The Homestake Mine seems certain to remain Homestake's principal holding regardless of the future results of the current exploration program. At Lead, miners are removing gold ore from depths of 7,400 feet and there are proven and probable reserves at these depths to last the next ten years. And this compares with some of the great South African mines now being worked down to 12,000 feet. To reassure its preeminence in domestic gold mining, however, Homestake has improved its exploration models and has developed new computer systems for deposit evaluation, feasibility studies and mine design. With the Homestake Mine, the McLaughlin discovery and a continuing long-term gold exploration program, Homestake expects to remain the leading domestic gold producer in the coming years.

Gold Prices In The United States

Major increases in world gold market prices during the free-market system of the past ten years have created attractive operating margins, and thus new incentives for gold exploration, development and mining in the United States. The magnitude of this renewed profit incentive is depicted on the historical chart (Figure 1) which plots gold prices against the U.S. Consumer Price Index (CPI), a measure of cost inflation in the United States.

History of U.S. Gold Price and Inflation Since 1792

The chart in Figure 1 shows that the federal government has "fixed" the U.S. currency value of gold under various forms of the gold standard for 160 of the last 190 years. Conversely, free-market forces have established the value of gold on just two occasions during the same period, spanning a cumulative total of 30 years.

The dollar value of gold was first maintained at a fixed price by the 1792 Mint Act which established a Bimettalic Standard (Ag , Au) for U.S. currency. The standard was based principally on silver in which the U.S. dollar was equated to .774 ounces of silver, with the mint required to maintain a fixed silver/gold ratio of 15:1. This established a fixed price of gold at $19.38 per ounce which was maintained until 1834 when the silver/gold ratio was changed to 16:1, elevating the fixed price of gold to $20.67 per ounce (Figure). This fixed price for gold persisted until 1861 when a free-market system called the "Greenback Era" prevailed during the events surrounding the Civil War.

The deflation following the Civil War caused prices to fall. In 1879, the U.S. government reestablished the fixed price of gold at the pre-war value of $20.67 per ounce, which continued through the inflation of World War I and the depths of the Great Depression. But in 1934, the government finally devalued the dollar by increasing the price of gold to $35 an ounce, restoring gold's purchasing power to near parity with U.S. currency (Figure 1).

The $35 an ounce gold price was retained by the 1944 Bretton Woods Agreement, which adopted a gold-dollar standard using the U.S. dollar as the official reserve currency for the newly established International Monetary Fund. Under this agreement, the U.S. dollar was defined as being 1/35 of an ounce of gold, and dollars and dollar credits held by foreigners were to be counted as reserves equal to gold. The U.S. would settle all foreign accounts with gold bullion payments and receipts. This action established the gold-backed U.S. dollar as a world reserve and stabilized international currencies until the 1960's, when various factors reduced the world's confidence in the ultimate ability of the United States to redeem its currency and debts in gold.

Some of the factors that undermined world confidence in the U.S. dollar were:

1) The rapidly increasing U.S. balance-of-payments deficits during the 1950's (Figure 2a);

2) The rapid growth of gold-backed U.S. dollars as international reserves (Eurodollar reserves) and resulting major extensions of bank credit (Eurodollar loan liabilities); and

3) Persistent inflation in the United States (decrease in real purchasing power of outstanding money balances and mounting federal debt).

This decreasing confidence in the dollar forced the London market price of gold to reach $40 [1] an ounce in October, 1960, when the U.S. balance-of-payments deficit exceeded the total value of U.S. government gold reserves at the fixed price of $35 an ounce (Figure 2a). As a result, foreigners increasingly converted their dollars to gold, reducing the U.S. government gold reserves from approximately 600 million ounces to about 300 million ounces between 1960 and 1968 (Figure 2b). In that year,

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1/ Price on the London Free Market for Gold, established for convenience in 1954.

the outstanding U.S. balance-of-payments deficit exceeded the U.S. gold reserve, valued at $35 an ounce, by 400 percent. Rather than devalue the dollar, the U.S. government stubbornly clung to the "official" $35 an ounce value of gold. For foreign central bank transactions, the U.S. Treasury exchanged dollars for gold at the "official" value. For other international transactions, the U.S. government recognized the free-market dollar value for gold (although at that time U.S. citizens were still not allowed by law to own gold bullion). This government policy established a "two-tier" gold pricing system in the United States.

The continuing weakness of the U.S. dollar as an international currency led to the establishment of a new international reserve system in January, 1970, comprised of Special Drawing Rights (SDR's -- paper gold), gold, dollars and foreign currencies. But foreign central banks continued converting U.S. dollars into gold at the "official" fixed price of $35 an ounce. By early 1971, the total of U.S. dollars in domestic circulation were only 25 percent backed by gold (actually, Congress had revoked the requirement for a 25 percent gold backing of U.S. currency as early as 1968). Again, rather than devalue the dollar, the U.S. government stopped the conversion privilege of dollars to gold in August, 1971, and allowed the value of the dollar to "float" on International money markets.

For the first time since 1879, the U.S. government had abandoned the gold standard (a fixed dollar value for gold). For the purpose of establishing its International Monetary Fund reserve positions, the U.S., in an agreement called the Smithsonian Accord, accepted devaluation of the U.S. dollar to $38 an ounce in December 1971. Again, for IMF purposes, the dollar was devalued to $42.22 an ounce in 1973. But the international pressures on the value of the U.S. dollar have not ceased. Since the Organization of Petroleum Exporting Countries' (OPEC) oil embargo in 1973, the United States' balance-of-payment deficits, federal debt, and domestic inflation rates have worsened markedly. To put this into some kind of perspective, were the United States to settle just one of its outstanding monetary obligations, its balance-of-payments deficit, with its current gold reserves, gold would have to be valued at $830 an ounce (Figure 2c).

World political tensions and uncertainties -- such as the OPEC oil embargo -- do affect free-market gold prices. The exile of the Shah of Iran and major increases in OPEC oil prices during 1979 drove the price of gold from $230 an ounce to $498 an ounce by mid-December. When in late December, 1979, the U.S. government froze Iranian assets in U.S. banks, the gold price for the first time exceeded $500 an ounce. By the time of the events surrounding the silver commodity market speculation debacle in March, 1980, gold prices had soared to $850 an ounce. The question remains as to whether there is a correlation between that top dollar value for gold and the corresponding balance-of-payments deficit value of $830 an ounce mentioned earlier. Whatever the correlation, when the Iranian tensions eased, oil became more plentiful, and the U.S. Congress passed the Reagan economic package to curb domestic inflation, gold prices dropped back to between $385 and $435 an ounce in August, 1981.

Incentives For Gold Exploration And Mining

For over 100 years, Homestake Mining Company has mined gold at Lead, South Dakota, both during those periods when there have been cost squeezes and when there have been favorable climates for gold mining. But the mining industry recognizes there have been times, historically, when investment in gold exploration and mining has been more reasonable than at others. The incentives for such investment are essentially: a) the ability to make a profit on the investment; b) improvements in exploration and mining techniques that make once-marginal deposits economical to process; and c) favorable prospects for the future purchasing power of gold.

Profit Incentives

A number of periods in our nation's history have provided profit incentives to find, develop and mine gold; on the other hand, fixed-price, inflationary-cost squeezes have often created disincentives to invest in gold mining. The 190-year relationship between U.S. gold prices and the U.S. Consumer Price Index (which, in a general way, reflects mining-cost inflation) provides a means to identify favorable and unfavorable periods in the history of U.S. gold mining. In general, except for a brief inflationary period between 1812 and 1816, an attractive investment climate existed for U.S. gold mining during the 123-year period from 1792 until 1915 because the long-term trend in costs generally paralleled changes in the gold price (Figure 3).

Strong inflation beginning in 1915 reversed the favorable price-cost relationship, since the price of gold remained fixed. This created an unfavorable climate for gold investments until 1934, when the offical price of gold was increased (dollar devalued) to $35 an ounce. Higher gold prices again provided profit incentives for gold mining until 1942, when the U.S. Production Board Order L-208 closed U.S. gold mines during World War II. This order was rescinded in 1945, but many mines did not reopen. Many of those that did reopen were forced out of business by 1962-63 due to high post-war inflation which pushed mining costs up while gold prices remained fixed (Figure 3). A major exception was Homestake Mining Company's Homestake Mine in South Dakota, which, except for the three-year government closure, has operated continuously since 1877. Other important exceptions include the Carlin and Cortez discoveries in Nevada which were placed into production in the 1960's because of relatively low operating costs attributable to bulk mining by open-pit methods. Overall, however, the investment climate for gold mining remained unfavorable from 1943, when gold mines were closed, until late 1971 when the United States abandoned the fixed dollar value of gold.

The free-market value of gold provided strong profit incentives for investment, when, in 1974, the price of gold reached $150 an ounce, establishing parity with the purchasing power of a depreciated U.S. currency (Figure 3). Since 1978, the incentives have been even greater because gold prices have exceeded U.S. currency depreciation for the first time in our history. In summary, favorable gold investment climates existed from 1792 to 1915, 1934 to 1943, and from 1971 to the present; unfavorable climates persisted from 1915 to 1971, with the exception of the ten-year period 1934-1943. Although the gold price has risen substantially, operating costs for the gold mining business have also increased. The average free world cost of production of gold is estimated at $215 an ounce, as of December 31, 1980.

Another financial indicator for the purchasing power of gold might be a comparison of the price performance of gold and of the stock market in the United States (Figure 4). Historically, the stock market has established a long-term growth rate, increasing at approximately 3 percent a year. Gold prices in dollars per ounce were higher than stock market averages from 1792 to 1830, overlapped the market from 1830 to 1890, were lower than the market from 1890 to 1980, and finally, have again overlapped the market since 1980.

Exploration Technology Improvements

Major advances in exploration technology have been achieved in the last 35 years for metals and minerals other than gold, but were not generally applied to gold because of the unfavorable investment climate that persisted. These advances include new geologic concepts, geologic models, and improved exploration methods, which have been used successfully in the search for porphyry copper, molybdenum, lead/zine, uranium, and for other mineral deposits. With an improved investment climate, these advances can now be applied with great advantage in gold exploration programs.

Other factors further enhance prospects for profitable gold investment in the United States. New types of gold deposits have been recognized, such as at Carlin, and provide new exploration targets. Improved processing methods, such as heap leaching and carbon-in-pulp recovery methods, may also provide lower operating costs and therefore improve the economic potential of some new projects.

U.S. Purchasing Power of Gold

The dollar price of gold is the measure of gold's purchasing power in the United States. Judgments concerning future dollar values of gold are germane considerations when assessing profit incentives to justify investments in exploration, development and mining of gold.

One approach to estimating gold's purchasing power in the United States is referred to as the "commodity value". This approach assumes that gold is simply a commodity and that its U.S. purchasing power is a function of the value of the dollar, as measured by the U.S. Consumer Price Index. Based on this Index (with 1967 = 100), the U.S. dollar value of gold should be $275 an ounce, the current CPI (Figure 1).

Other values of gold come into play when considering its purchasing power since gold represents wealth and can be used as a reserve in support of paper currencies and government debt. Another method, therefore, of estimating the dollar value of gold can be conveniently termed the U.S. monetary value" of gold, implying the U.S. purchasing power of gold is related to such economic variables as the U.S. money supply (M1, M1B, M2, etc.), the federal debt, the U.S. balance-of-payments deficit, etc. These "monetary values" of gold can be calculated by dividing the quantity of each by the gold reserves held in the United States Treasury. These values will obviously change almost daily as the Federal Reserve and Treasury positions change.

Assuming only a 25 percent backing by gold reserves, the current "money supply (M1B) value of gold" would be $407 an ounce; the "federal debt value", $923; and the "U.S. balance-of-payments deficit value", $207 (Figure 5). Of course, if these monetary values were to require 100 percent gold reserve backing, the gold prices in U.S. dollars for each category would be four times greater than those values listed above.

Historical trends for U.S. money supply, federal debt, and U.S. balance-of-payments deficits are plotted in Figures 6 and 2. The historical trends for "monetary value of gold" for each of these U.S. government liabilities are shown in Figures 7a, 7b and 7c. It is interesting to note that the base gold price during the last nine years has exceeded the "U.S. balance-of-payments deficit value" of gold, assuming the deficit is backed by a 25 percent gold reserve. On the other hand, the highest free-market price for gold ($850 an ounce), achieved in 1980, correlates to the "U.S. balance-of-payments deficit value" of $830, assuming backing by a 100 percent gold reserve. At 25 percent coverage, the "federal debt value" of gold of $923 an ounce somewhat exceeds the highest free-market price for gold attained to date.

If, as some economists assume, a minimum responsible gold coverage would be a 25 percent backing for outstanding money supply (M1B) plus our balance-of-payments deficit, the current purchasing power of gold in the U.S. would be about $614 an ounce (Figure 5). Should confidence in the U.S. dollar totally collapse, the 100 percent backing for the money supply and balance-of-payments deficit value of gold would approach $2,450 an ounce (Figure 5). Of course, similar calculations for the purchasing power of gold for other countries would result in different values, based on their reserves and monetary liabilities, so that gold values continutally vary from currency to currency.

Consideration of Returning to the Gold Standard

Recently, economic discussions have keyed on the possibility of returning to the gold standard to cure the country's economic ills. The U.S. Federal Reserve defines the "gold standard" as the commitment to establish a fixed relationship between currency and a specified amount of gold. By this definition, the U.S. has been on the "gold standard" for 160 of the last 190 years. The long-term trend lines for inflation rates averaged 0.2 percent a year during the 123 years from 1792 to 1915 and changed dramatically to 3.3 percent a year for the 66 years from 1915 to 1981 (Figure 8a). What were the causes of this change of rate of inflation in 1915?

The change took place when the country was on the gold standard, which, according to proponents of the gold standard as a cure for inflation, should not have happened. The gold standard, clearly, did not prevent the change in the rate of inflation.

Historical evidence suggests that long-term inflation rates respond to governmental policies and actions that cannot be prevented by a gold standard. One of these actions was the formation of the Federal Reserve System in 1914, which marked the beginning of permanent accelerating federal debt, increasing at an average long-term rate of 7.0 percent a year between 1914 and 1981 (Figure 6). Economists agree that excessive government spending, creating federal deficits, results in inordinate demands for goods and consequently forces increases in prices for those goods. Another government policy that directly influences inflation is the policy of federal income taxation, initiated in 1913. The taxation of corporate income results in higher prices for products to maintain investment returns at acceptable levels. Nonetheless, the rate of taxation has increased steadily. These two government policies clearly influence rates of inflation -- influences that would not be prevented by reestablishment of a gold standard.

The initial maximum tax rate was 7 percent, without distinction between capital gains and earned income. By 1981, the top tax rate on personal earned income was 50 percent; unearned income, 70 percent; and corporate income, 48 percent. U.S. individual and corporate income tax rates have increased at a rate of 3.4 and 4.2 percent a year, respectively, since 1913 (Figure 8b). Actual federal income taxes collected have increased at a rate of

6.5 percent a year since 1913. The basic causes of inflation are clearly unrelated to the gold standard, and just as clearly related to increasing federal debt and higher income taxes. History shows that the gold standard does not prevent or cure inflation. The free-market price for gold, however, does appear to be a measure or indicator of the success of a government's efforts to control or cure inflation.

Development Of Homestake's U.S. Gold Exploration Program

Homestake's long-term historical business emphasis and commitment to profitable gold exploration, development and mining were reinforced during the development of a new corporate growth plan in 1978. New profit incentives, geological advances and exploration opportunities justified accelerating our exploration program to capitalize on Homestake's existing expertise in a timely manner. The following discussion is an overview of Homestake's U.S. exploration objectives, strategy and results to date.

Exploration Objectives

A number of criteria were considered in formulating Homestake's U.S. gold exploration objectives. Included among them are:

1) Consideration of size and economic parameters;

2) Geology and geologic types of world gold deposits;

3) Appropriate levels of exploration efforts;

4) Budgeting and scheduling of an effective exploration program; and

5) Projected exploration risks and rewards.

Size and Economic Parameters

Homestake's corporate plan emphasizes maintaining and strengthening its position as the premiere U.S. gold mining company. We therefore concentrated our efforts towards discovery of large deposits that would substantially enhance Homestake's U.S. gold production and earnings.

The major objectives of the U.S. gold exploration program were to discover:

1) Gold reserves containing 3 million ounces (a major deposit) within ten years;

2) Gold reserves containing 1.5 million ounces (a substantial deposit) within five year; and

3) Gold reserves containing a minimum of 0.5 million ounces (an acceptable deposit discovered by "fallout" from the search for larger reserves).

The internal rate of return considerations, summarized in Figure 10, require that we find relatively low-cost mines (in the lower half of the cost curve) and relatively high-grade deposits suitable for bulk surface or underground mining. For open-pit mining, our objectives focus on deposits with ore grades exceeding 0.15 ounces per ton; for underground mining, grades exceeding 0.3 ounces per ton.

Geology and Gegologic Types of Gold Deposits

Homestake geologists studied major world gold deposits, classifying the known deposits according to their geology, size and grade, and from this data determined the desirability of each of our exploration programs in the United States. The geological types of major gold deposits identified in the study are shown in Figure 9. The contour lines represent total contained ounces of gold in a deposit and provide a quick reference to the overall size and importance of each geologic type of gold deposit. The largest gold deposits of the world are the Witwatersrand type Fossil Placer Deposits of South Africa, which contain grades ranging from 0.10 to 0.50 ounces per ton, with ore tonnages ranging from 100 million to over 1 billion tons.

After studying the economics, size and grade objectives and the geological occurrences of the various gold deposits likely to occur in the United States, Homestake decided to search for Homestake-type and Stockwork-disseminated deposits in the United States. We also decided to conduct geologic research on gold to develop new geologic concepts that would lead to the discovery of new types of gold deposits of substantial size and grade to meet our corporate objectives.

Level of Exploration Program

The next step was to formulate the exploration program and determine the extent of the exploration effort in terms of budget and manpower. To accomplish this, we analyzed cost data and probability factors for each of the recognized sequential stages of mineral development. The stages include: reconnaissance, target exploration, deposit development, plan construction/mine development and production.

The costs of each activity within each stage of exploration and development were estimated from Homestake's exploration experience and records. In order to determine probable success ratios to apply to a gold exploration program, Homestake decided to use the empirical approach based on prior experience. Published data and privately developed data on the success ratios of gold and other metal exploration programs in the United States and Canada from 1000 to 1976, representing a wide range of success ratios, were compiled. Examples of several such studies are shown in Figure 11. Probability analyses were then conducted on the data to provide the statistical framework to develop Homestake's empirical probability models for the number of activities that would be required in each exploration stage to accomplish the discovery of an economic deposit of a given size. The results of two such analyses, one for a 50 percent probability of success and the other for a 75 percent probability of success, are summarized in Figures 12 and 13.

Once the probability model for a given size of deposit was available, the cost estimates for each exploration activity were used to determine the cost of exploration programs for a wide range of probabilities for a given deposit size (Figure 14). For example, we estimated it would cost $30 million to search for and find a deposit that would produce 150,000 ounces of gold a year for ten years; that was for a probability of 75 percent. To put that figure in perspective, we established it would cost $22 million for a 50 percent probability of success, and $16 million for a 30 percent probability of success.

It is important to note for a given budget expenditure, exploring for a single metal, such as gold, has a higher probability of success of a discovery than does the probability of finding gold in a multi-metal search with the same budget (Figure 15). It follows that similar studies be conducted to develop exploration programs for each metal in a proposed multi-metal search effort. The timing of exploration expenditures must also be considered, both from the standpoint of the resources of the exploring company, availability of qualified personnel, and the competitive situation.

Formulation of Homestake's exploration program included all of the above factors in determining its U.S. gold exploration program. Homestake's projected probabilities, costs and timing of its exploration program are summarized in Figures 16 and 17. These charts show that substantial expenditures must be made to test a larger number of targets to achieve the high probability of success in gold exploration desired by Homestake. Homestake's projected gold exploration expenditures and projected returns (i.e., risk/reward ratio), based on achieving the five-year program objectives, are summarized in Figure 18.

Implementation of Homestake's Gold Exploration Program

Exploration Management -- Functional Organization

To take maximum advantage of Homestake's in-house expertise to achieve the major objectives of the new growth plan, the exploration team was reorganized in November 1978 to manage by exploration function rather than by geographic location. The specific functional exploration activities include reconnaissance, target exploration, deposit development, and land acquisition-administration (Figure 19). The managers of these activities are responsible for developing plans and budgets, quality and quantity standards, programs and organization to achieve the desired results for their functional areas, regardless of the geographic location. For instance:

1) The Gold Reconnaissance Manager is responsible for the search and selection of favorable areas, detailed appraisals of favorable areas, and the selection and prioritization of a queue of target areas, as well as land acquisition to control target lands. High priority targets are transferred to the Target Evaluation Manager for further evaluation. Lesser priority properties are retained in a queue for future consideration by reconnaissance.

2) The Target Exploration Manager is responsible for initial exploration testing to evaluate specific target areas. If preliminary results and economic estimates are encouraging, this manager is responsible for conducting additional exploration to delineate the deposit

and to conduct preliminary engineering, metallurgical testing and economic appraisals. High priority properties are transferred to the Deposit Development Manager. Again, lesser priority properties are retained in a target queue

3) The Deposit Development Manager is responsible for bulk sampling, pilot plant testing, metallurgical and engineering appraisals, conceptual mine and plant design and for preparation of a preliminary feasibility study. High priority properties with acceptable size and economics are transferred to the Homestake Operations management for mine development, plant construction and production.

4) The Land Acquisition-Administration Manager is responsible for acquiring land control and administering land contracts. This manager provides these services to the other exploration managers in coordination with corporate policy.

Conceptual Reconnaissance

The conceptual approach to reconnaissance has been utilized in place of the more conventional geographical approach. Under this system, reconnaissance teams pursue specific types of gold deposits in any favorable area. Applied geologic research is conducted to: refine geologic models and search areas with potential for well known types of gold deposits; develop geologic models and search areas for poorly known or poorly understood gold deposits; develop theoretical concepts and techniques to search for new types of gold deposits; and improve performance and decision-making at each functional stage of exploration (Figure 20).

Prioritized Queue of Properties at Each Exploration Stage

The development of a prioritized queue of prospects for each stage of exploration has been an essential element of Homestake's exploration program since this system provides an opportunity to identify "fast-track", high priority projects, leaving lower priority prospects in an inventory classification for future consideration.

Priority ratings are assigned to properties by estimating the geologic probability of occurrence of commercial gold deposits which conform to the objective of the exploration program. Criteria used to make these priority evaluations include: a) the presence of a geologic trap (favorable structural setting or favorable permeable host rock), b) evidence of a gold source (presence of ore grade or anomalous gold values, or in some cases, pathfinder elements), and c) the presence of favorable alteration systems (alteration assemblage related to a geological model for a given type of gold deposits.)

After the geologic probability assessment for each prospect is estimated, the cost of arriving at the next decision point for each prospect is determined. Risk factors and present value estimates are then determined for each property and a priority established. By updating priorities at each decision point for a project, we are able to continuously prioritize projects at all stages of the exploration sequence.

During the first year of exploration under this system, Homestake emphasized the development of a reconnaissance queue of prospects. At the end of the first year, we had identified enough high-priority properties to begin our target exploration programs. Target evaluation during the second year generated a deposit development project and also resulted in identification of several targets requiring intensified target evaluation efforts. Deposit development continued on a high-priority project during the third year. In addition, we continued fine-tuning of our reconnaissance, target exploration and management systems.

Homestake's Exploration Program Results

Homestake has been very fortunate early in its exploration program to realize the soundness of the theoretical concepts. The company discovered and began development of a major discovery within the first two years of the exploration program. This compares quite favorably with our hopes and expectations. Homestake's five-year and ten-year exploration objectives in the United States are summarized in Figure 17; our plans to date and results to date, in Figure 21. The McLaughlin gold deposit, located in a remote area of Northern Napa County, California (Figure 22), was discovered during the second year of our exploration program. This deposit contains announced reserves of 3.2 million ounces (20 million ounces at 0.16 ounces of gold per ton) and is obviously a major addition to Homestake's gold reserve portfolio. This discovery achieved two of our exploration program goals:

1) The deposit meets the objective of our ten-year program, i.e., the discovery of an ore deposit containing 3 million ounces in gold reserves; and

2) Discovery of a new geologic type of gold deposit, using new geological models and concepts.

The McLaughlin deposit may best be described as a Stockwork gold deposit in volcanic and sedimentary rock, suitable for open-pit mining. In addition, we foresee the possibility for an underground mine operation on higher-grade gold ore below the estimated pit limits. The cost to discover and develop the McLaughlin property, together with establishing a queue for more than 60 properties in various stages of evaluation, amounts to $28 million to date, or approximately $9 per ounce of announced gold reserves at the McLaughlin deposit.

United States Open-Pit Published Gold Reserves

An analysis of published open-pit gold reserves in 19 deposits in the United States illustrates that a large number of deposits have been discovered, expanded and resurrected during the last five years. The total U.S. open-pit-type gold reserves as of September 1, 1981, are estimated at 242 million tons of ore at a grade of 0.076 ounces of gold per ton or 18.5 million ounces of gold. Gold grades range from 0.03 to 0.22 ounces of gold per ton, with tonnages ranging from 1 million to 65 million. The average deposit is estimated to contain 12.7 million tons of ore at 0.076 ounces of gold per ton, or approximately 1 million ounces of gold.

Summary and Conclusion

The profit potential for gold mining investments due to the free-market prices of the last decade -- after nearly 65 years of adverse fixed-price, high-inflation margine squeezes -- has provided new incentives for gold exploration, development and mining. Major advances in exploration technology that have been developed and successfully used in other metals and minerals exploration since World War II have not been intensively applied to gold exploration because of the adverse investment climate for gold. To take advantage of these new economic and technological incentives, Homestake developed its current exploration strategy and objectives in 1978. A major exploration program based on new geologic concepts, probability analyses, and a functional approach to exploration management was implemented in 1979. The objectives included discovery of a major 3.0-million-ounce gold deposit within ten years, and a 1.5-million ounce deposit within five years. Our board of directors committed to an exploration budget of approximately $12 million a year for five years, a major commitment for Homestake at a time when corporate earnings were at $31 million a year (1978). This was a daring commitment, but the board expressed its confidence -- in dollars and cents -- in the expertise Homestake had developed in exploring, developing and mining for gold during its 100 years as the nation's largest gold producer.

The program met with early success in the fall of 1980 with the discovery of the 3.2-million-ounce McLaughlin gold deposit in California. The deposit has been named after Dr. Donald H. McLaughlin, the 89-year-old retired chairman and still a director of Homestake Mining Company. It was Dr. McLaughlin, who, as a geologist in the 1920's, played a key role in expanding the known gold reserves in the Homestake Mine in South Dakota. The McLaughlin discovery has to be attributed to the efforts of a fine, dedicated, professional exploration team. It achieved at the end of the second year Homestake's ten-year exploration program goal. This, we admit, was partly luck, but also a result of Homestake's excellent and extensive geological files which aided in rapid development of new geologic concepts.

The long-term commitment to new exploration ideas and approaches by Homestake's executive management and directors has provided excellent support for our exploration efforts. Our early success and our on-going search for new deposits will keep Homestake Mining Company in the forefront of gold production and expertise in the United States for years to come.

FIGURE 1

THE FINANCIAL RECORD

1789 - 1981

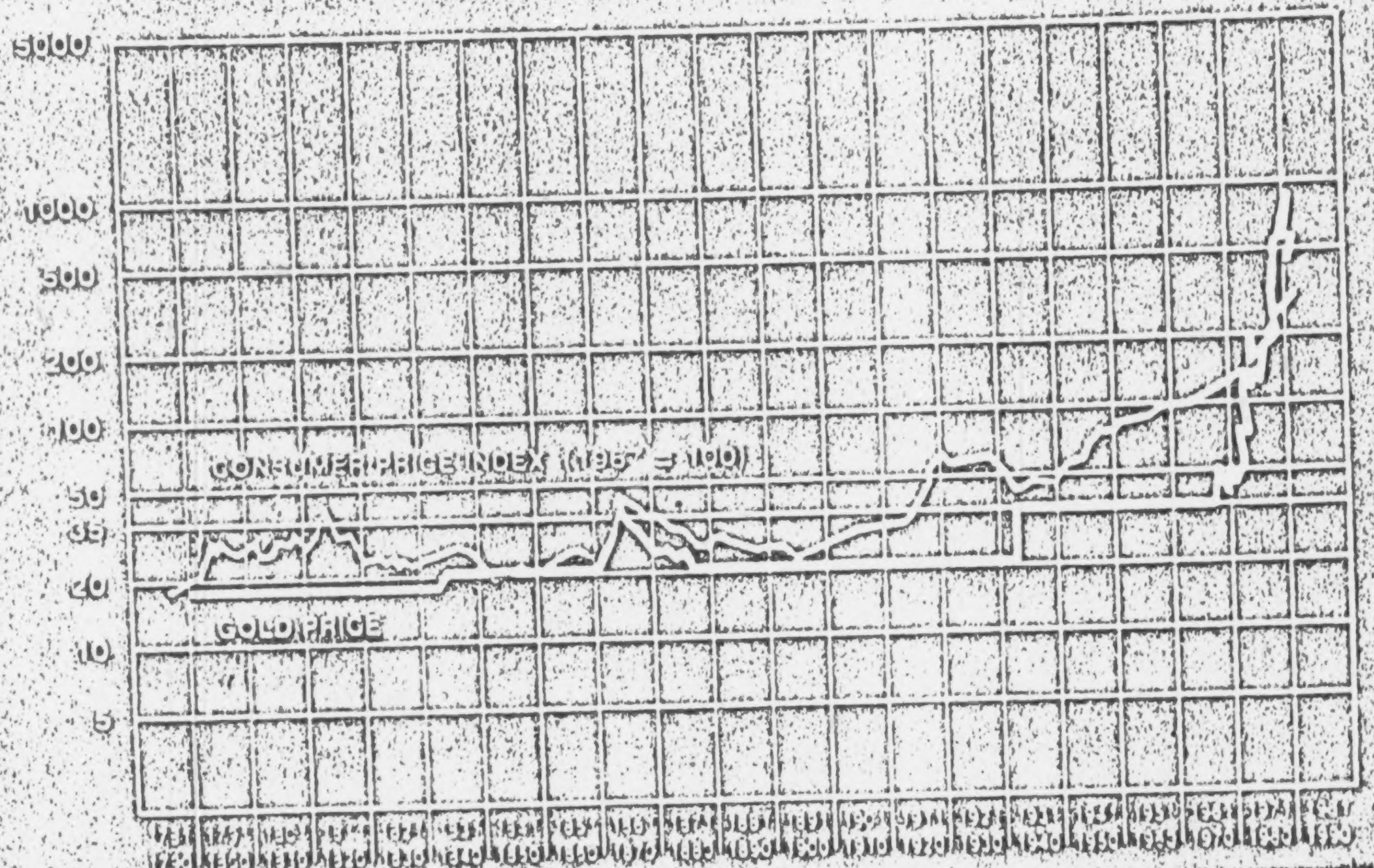


FIGURE 2a

THE FINANCIAL RECORD

1789 - 1981

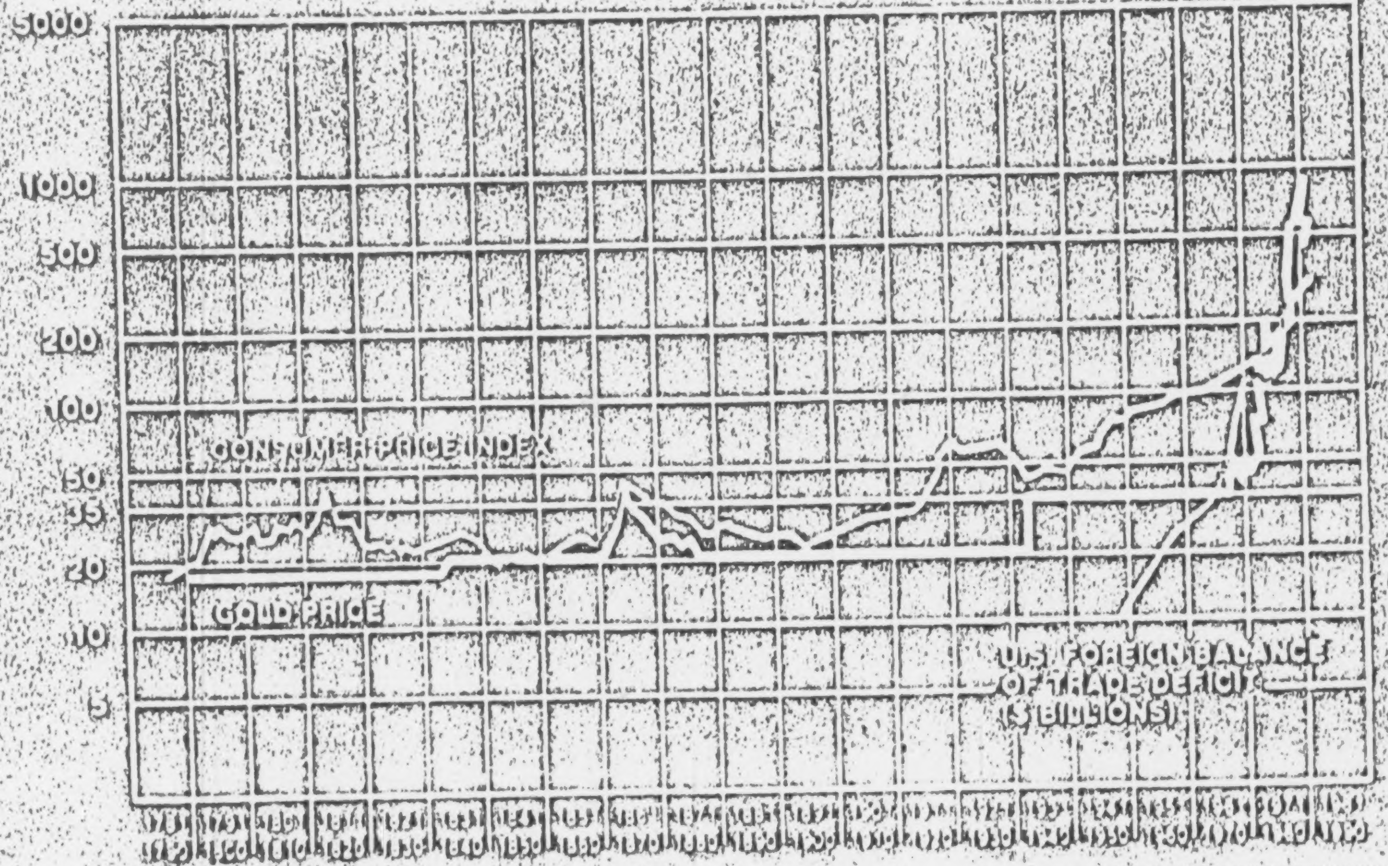


FIGURE 2b

THE FINANCIAL RECORD
1789 - 1981

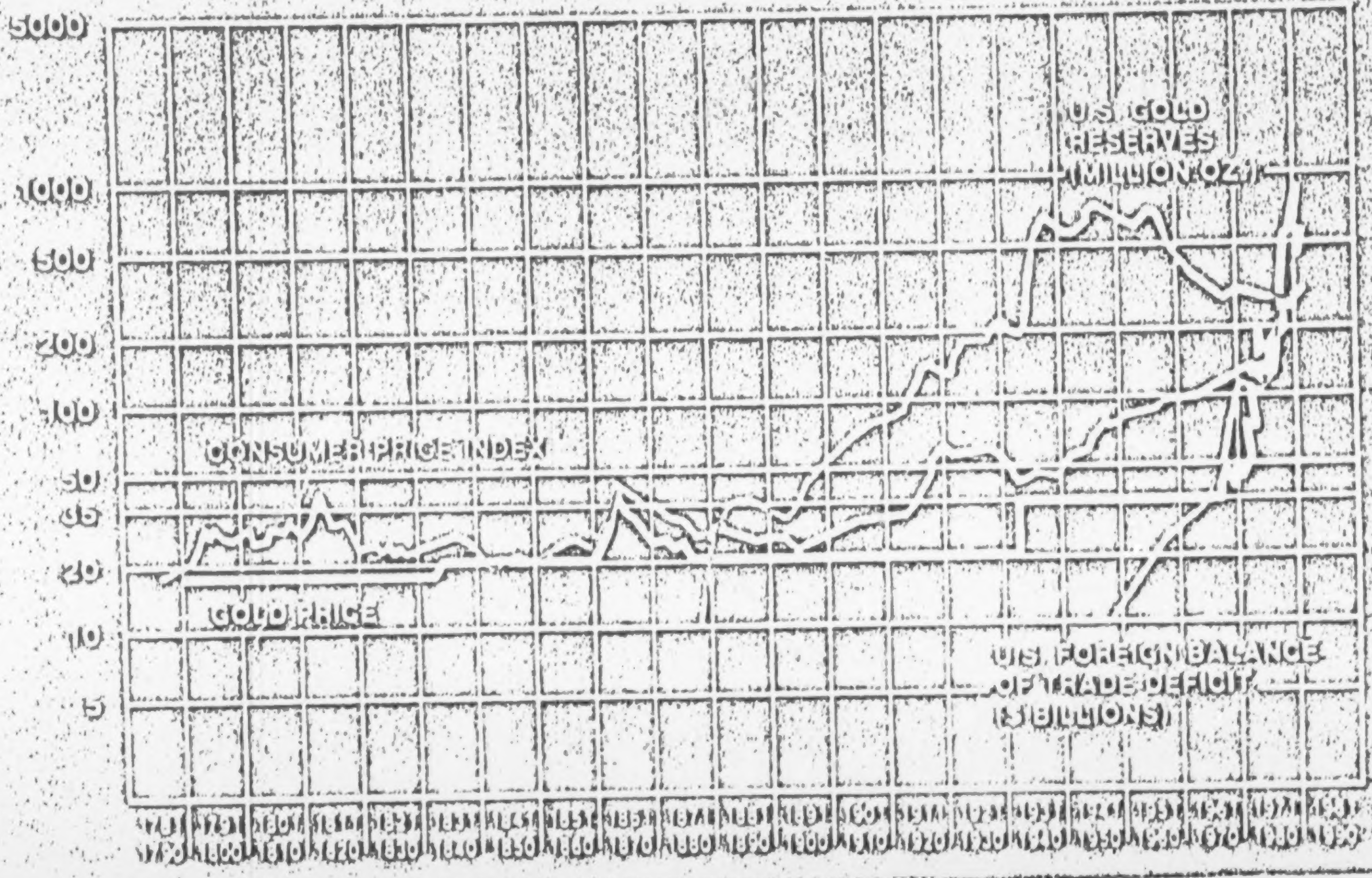


FIGURE 2C

THE FINANCIAL RECORD
1789 – 1981

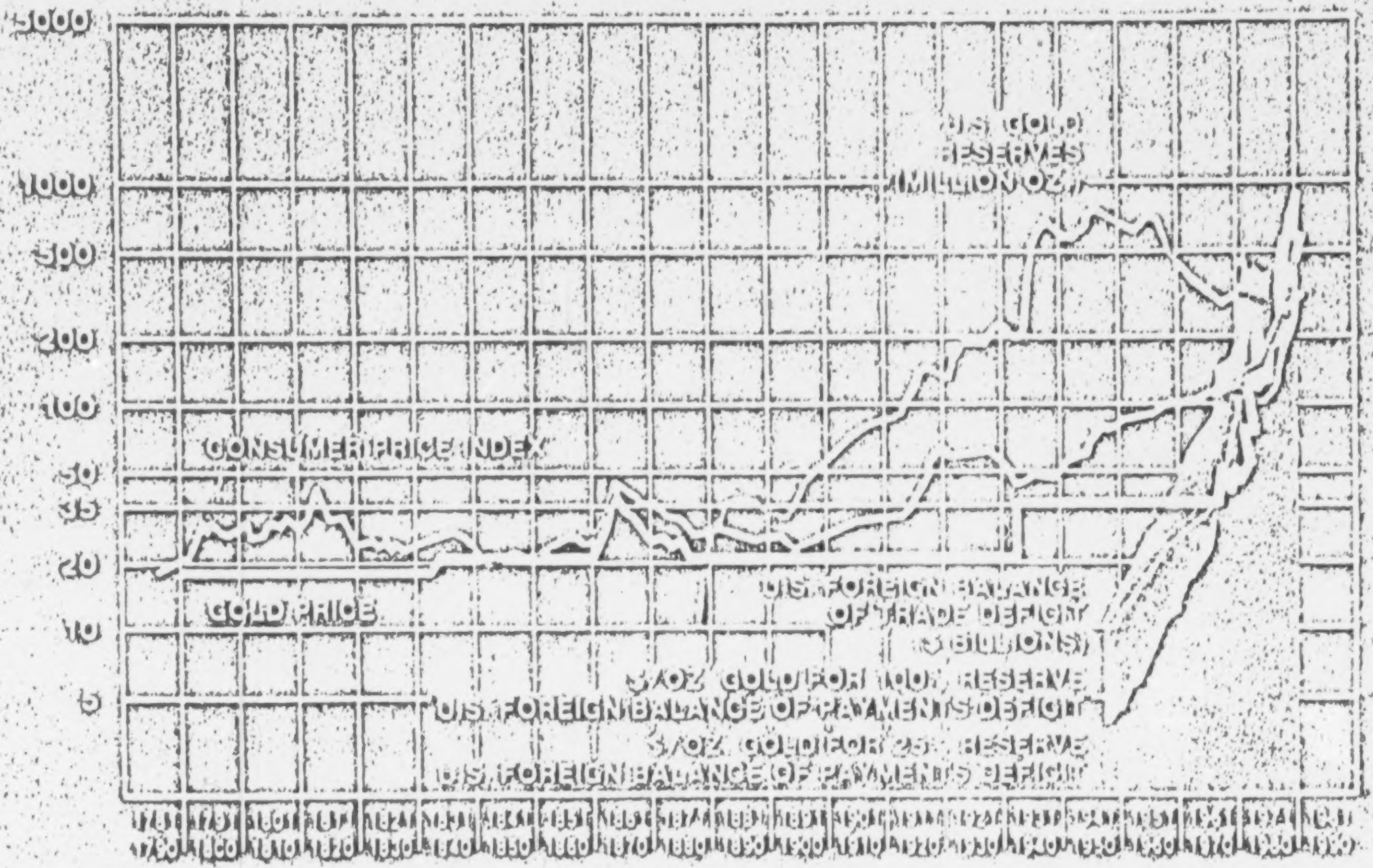


FIGURE 3

THE FINANCIAL RECORD
1789 - 1981

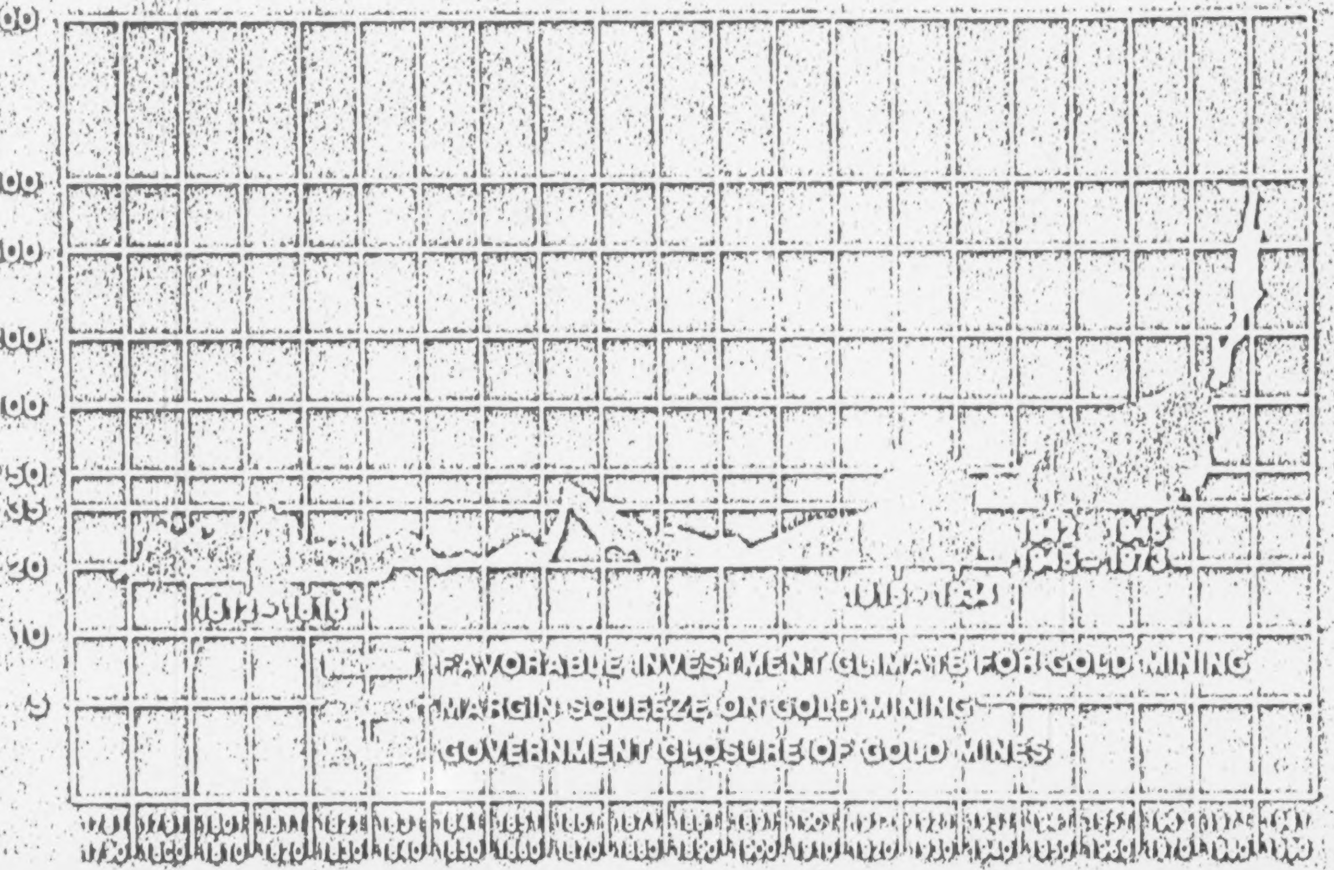


FIGURE 4

THE FINANCIAL RECORD
1789 - 1981

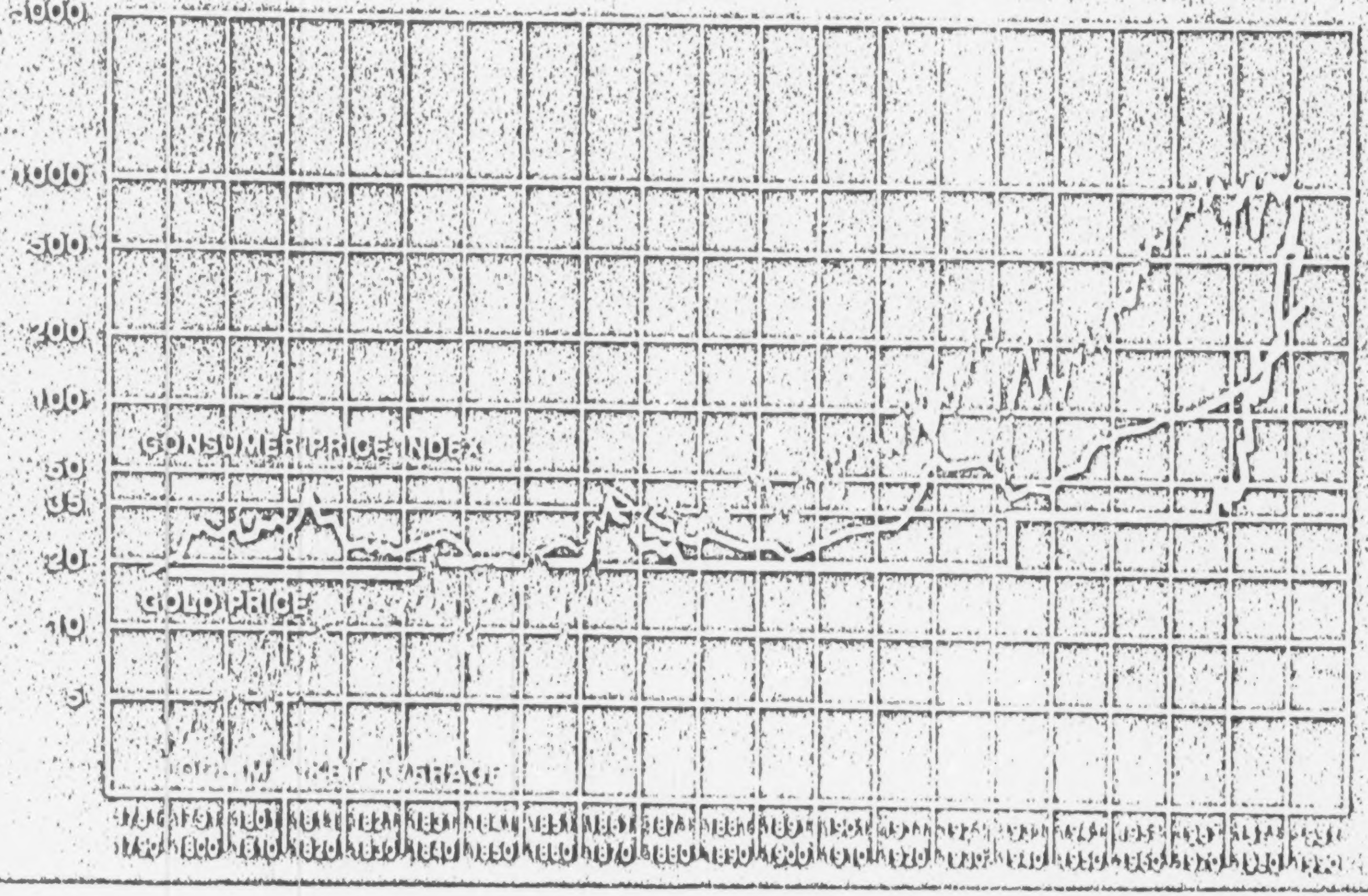


FIGURE 5

U.S. Treasury
Gold Supply . . . . 264.2 Million Ounces

		Dollar/Ounce Gold	
		25% Reserve	100% Reserve
Federal Debt ★	$976 Billion	$923	$3,694
Money Supply (M1B)	$430 Billion	$407	$1,627
U.S. Foreign Balance of Payments Deficit	$219 Billion	$207	$ 829
Money Supply + U.S. BOPD	$649 Billion	$614	$2,456

★ as of Sept. 1, 1981

FIGURE 6

THE FINANCIAL RECORD
1789 - 1981

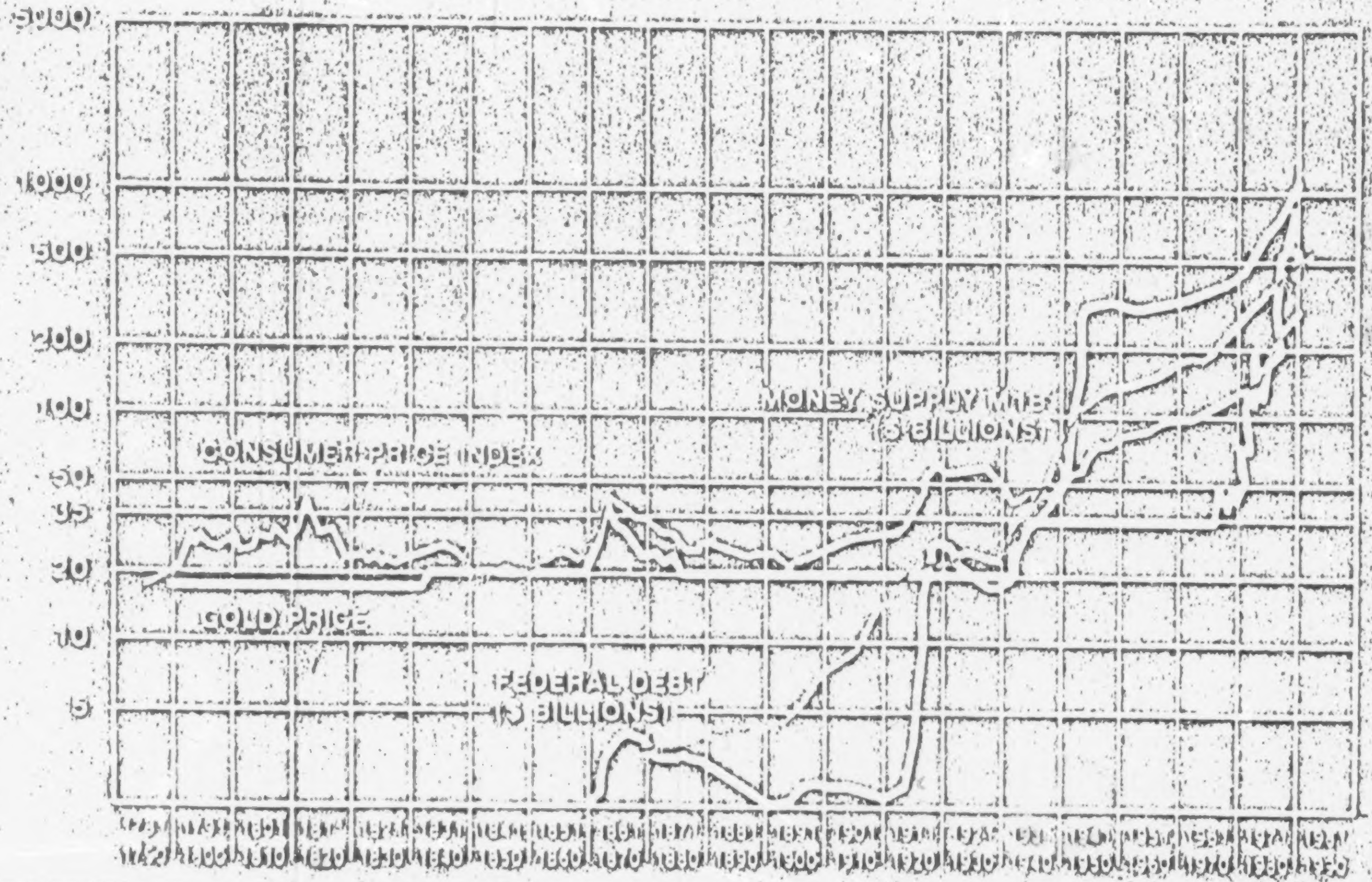


FIGURE 7a

THE FINANCIAL RECORD
1789 - 1981

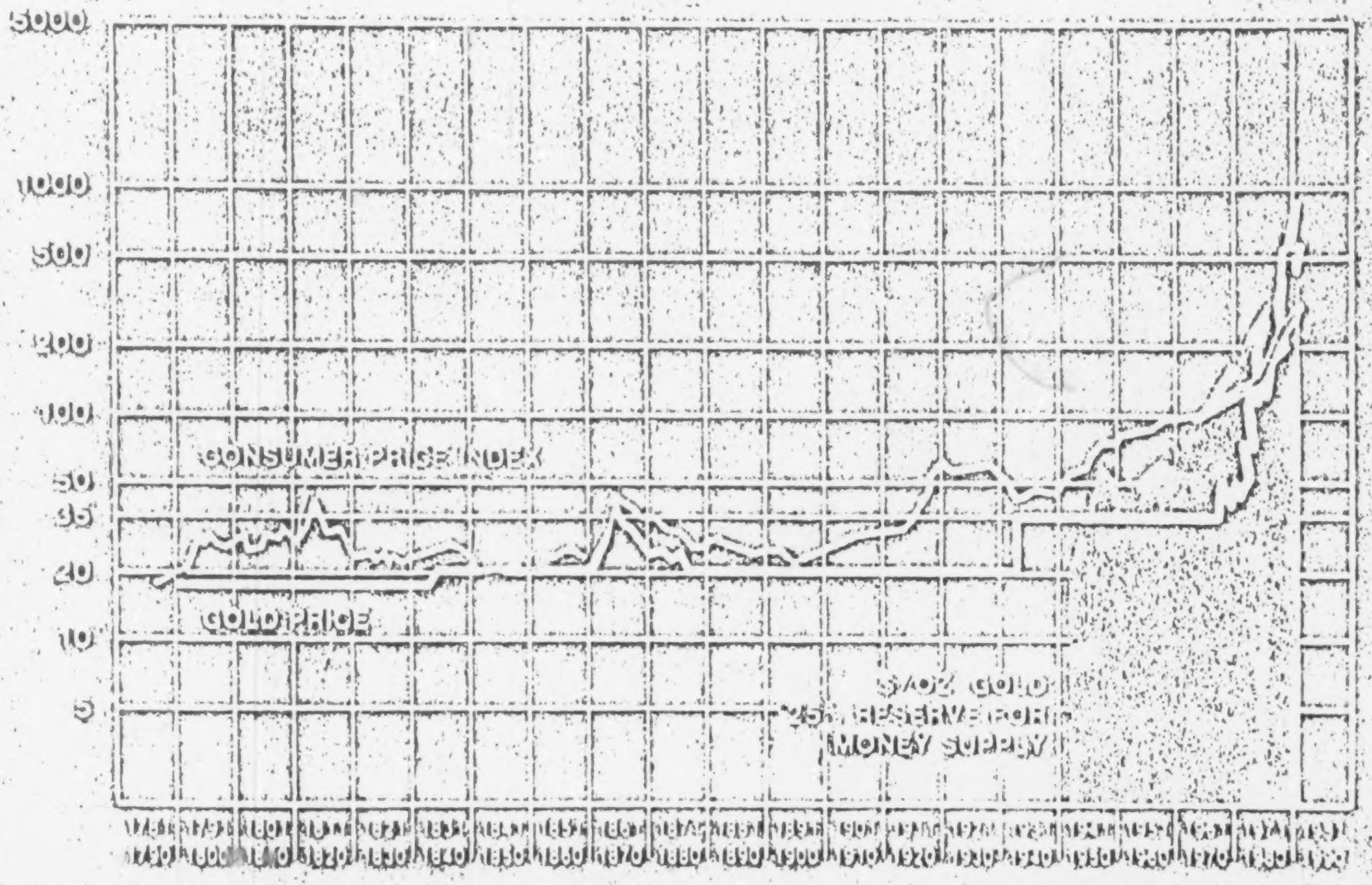


FIGURE 7b

THE FINANCIAL RECORD

1789 – 1981

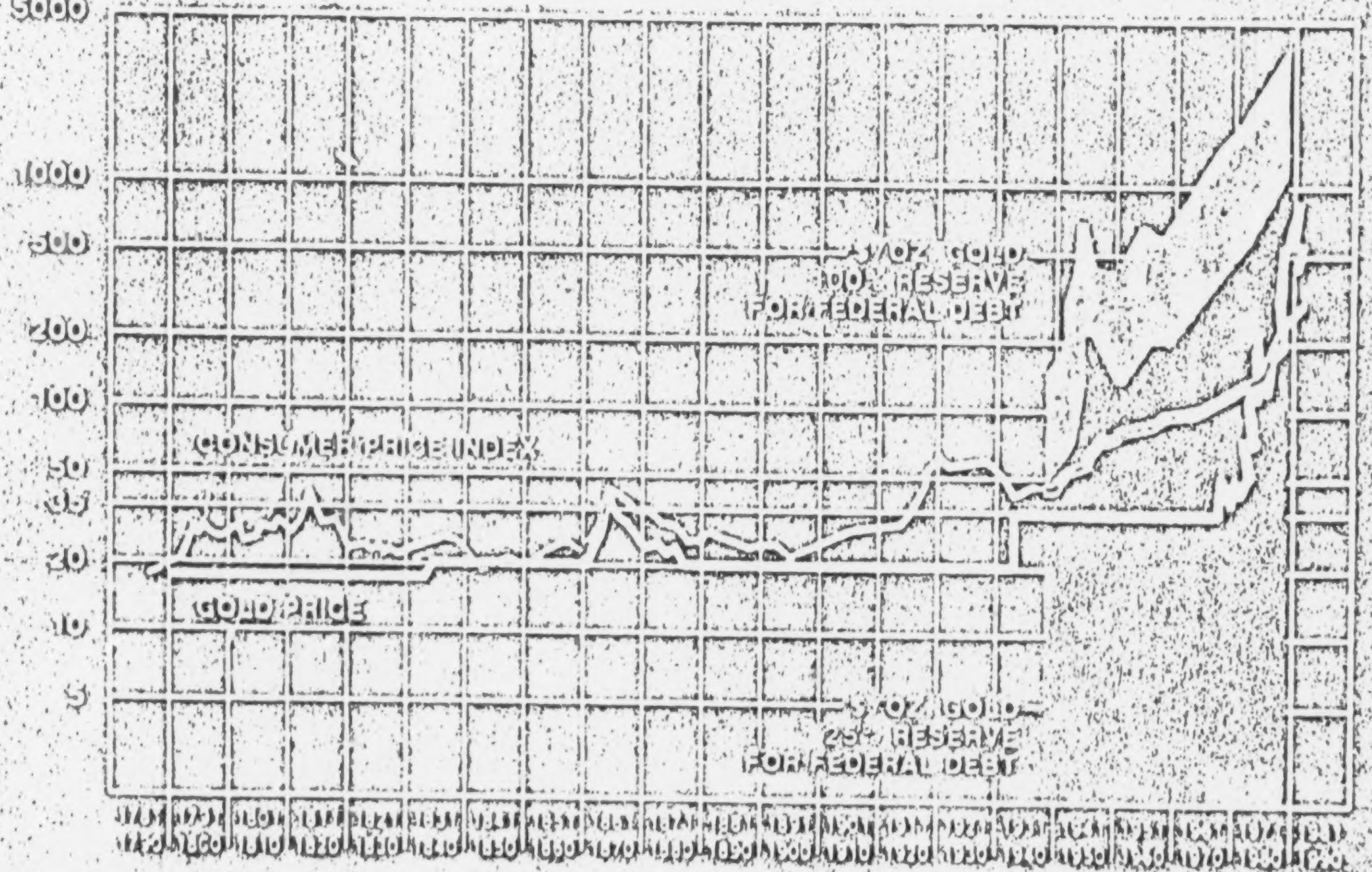


FIGURE 7C

THE FINANCIAL RECORD
1789 - 1981

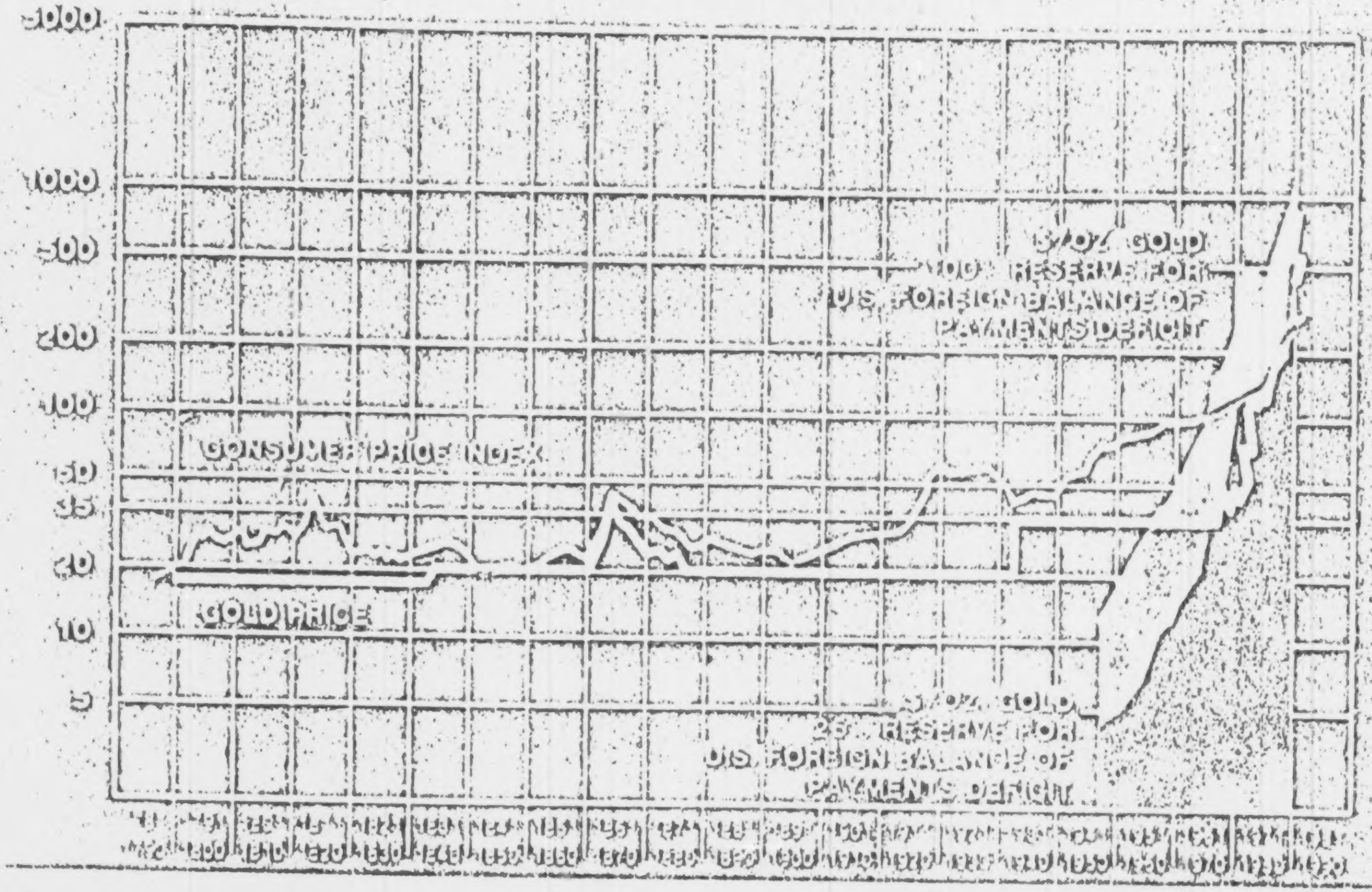


FIGURE 8a

THE FINANCIAL RECORD

1789 - 1981

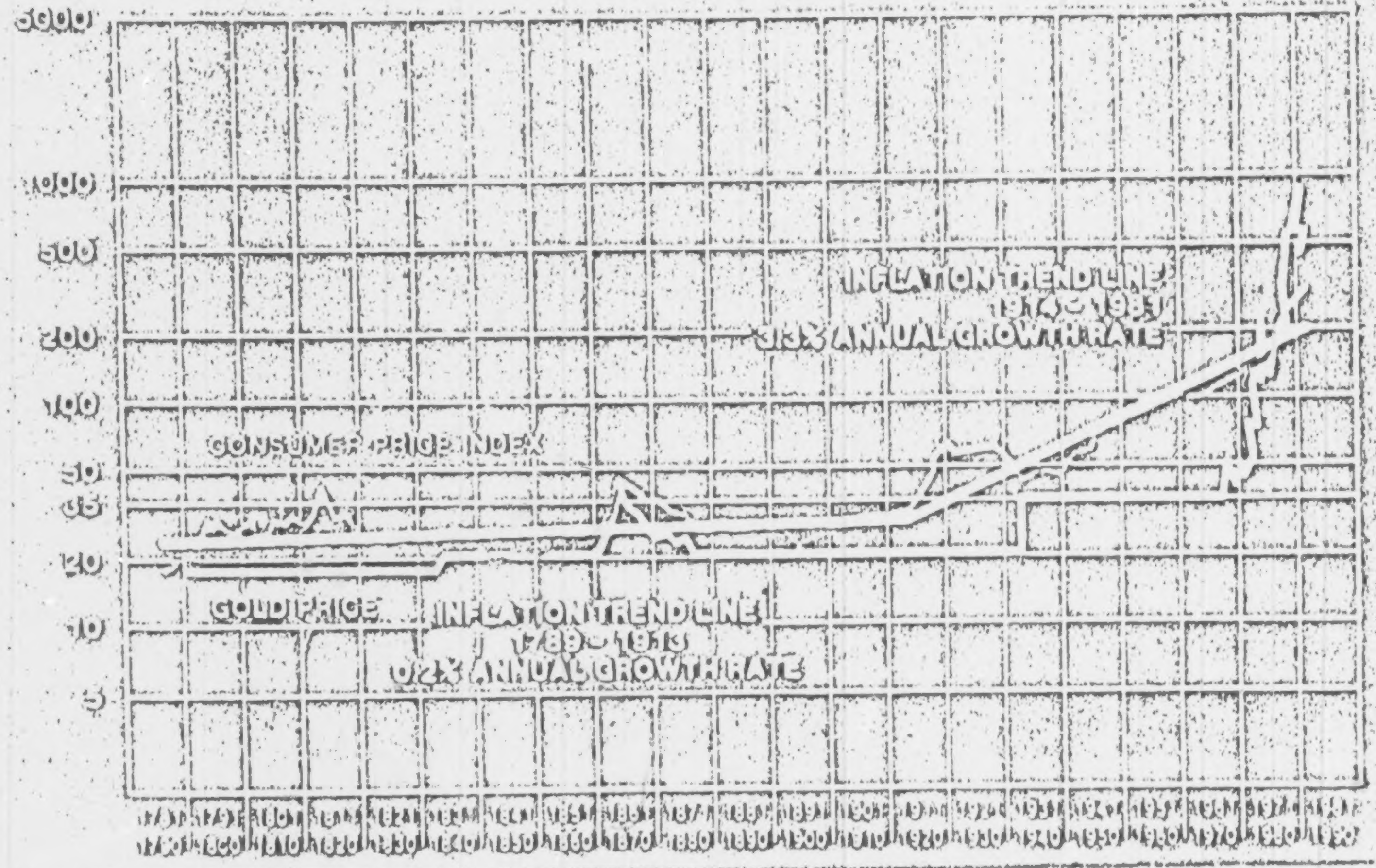


FIGURE 86

THE FINANCIAL RECORD
1789 - 1981

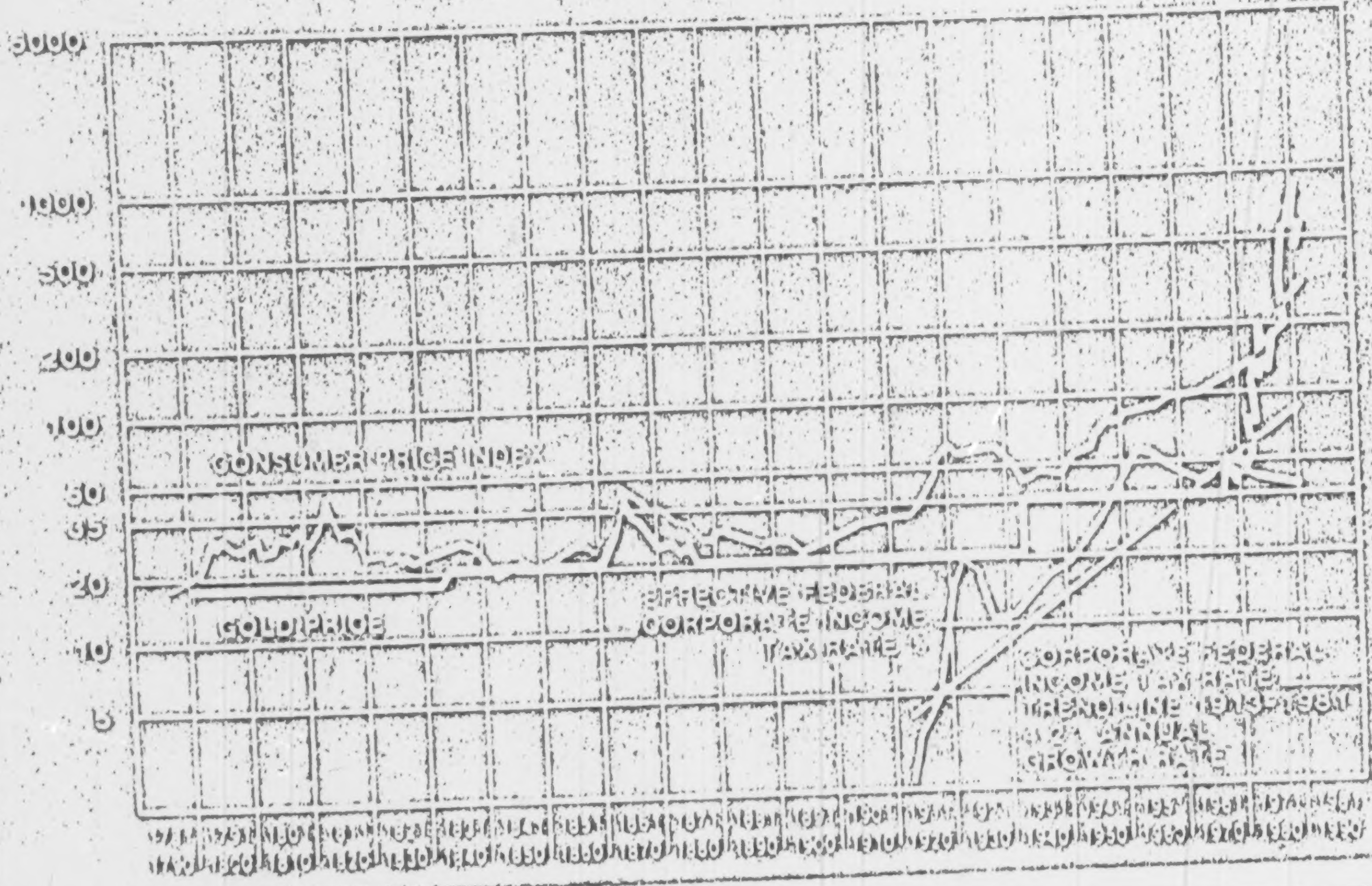


FIGURE 9

TYPES OF MAJOR WORLD GOLD DEPOSITS

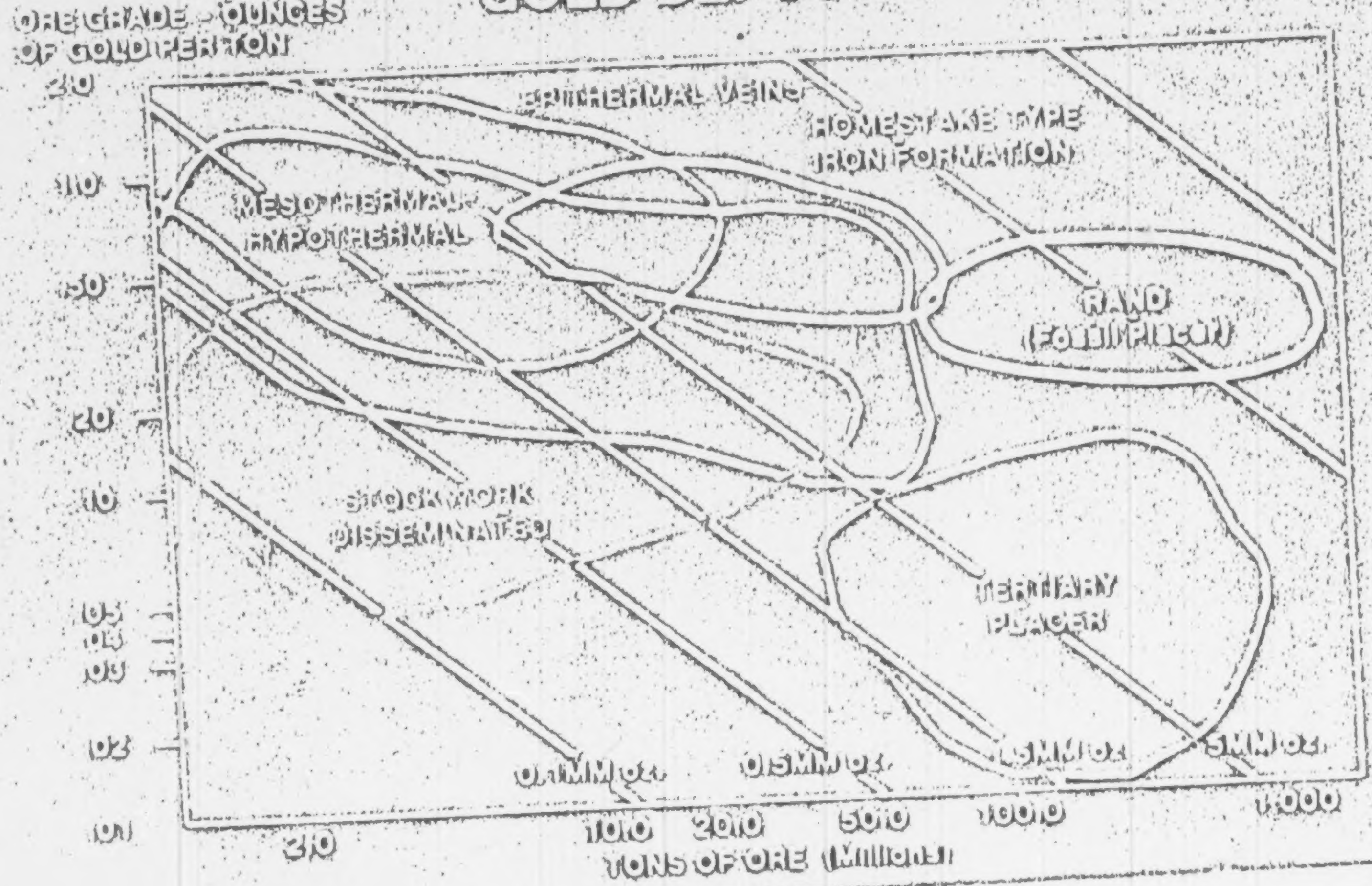


FIGURE 10

HOMESTAKE
GOLD EXPLORATION PROGRAM
ECONOMIC ASSUMPTIONS

- Minimum 15% Internal Rate of Return
- Deposits have minimum 10 year life.
- Definitions:
  - —ECONOMIC SUCCESS is a deposit containing 500,000 oz. gold.
  - —SUBSTANTIAL SUCCESS is a deposit containing 1,500,000 oz. gold.
  - —MAJOR SUCCESS is a deposit containing 3,000,000 oz. gold.

FIGURE 11

U.S. METAL EXPLORATION SUCCESS RATES

	AMC Survey of 41 Large Mining Companies (6 Years, 1970–75)		Private Survey of 9 Major Firms (Pre-1958 Thru 1966)		OTA Survey of 12 Major Firms (10 Years, 1970–76)	
	Number	%	Number	%	Number	%
Reconnaisance	5,718		732		?	
Target Exploration (Drilling Project)	536		165		451	
Deposit Development	83	15	19	12	32	8
Substantial Economic Deposit	?		3	2	19	4

% = % of targets advancing beyond drilling stage

FIGURE 12

GOLD EXPLORATION PROBABILITY LEVELS

50% CERTAINTY

	Contained Ounces Gold		
	500,000	1,500,000	3,000,000
	Number of Targets		
Reconnaissance Examinations	56	280	560
Target Evaluations	8	40	80
Ore Target Evaluations	2	10	20
Deposit Development	1	1	1

FIGURE 13

GOLD EXPLORATION PROBABILITY LEVELS

75% CERTAINTY

	Contained Ounces Gold		
	500,000	1,500,000	3,000,000
	Number of Targets		
Reconnaissance Examinations	100	500	1,000
Target Evaluations	10	50	100
Ore Target Evaluations	2	10	20
Deposit Development	1	1	1

FIGURE 14

GOLD EXPLORATION PROGRAM

EXPLORATION BUDGET
(In Millions of Dollars)

Ten-Year Production (Million Oz.)	Certainty Level		
	75%	50%	30%
.5	$ 7	$ 6	$ 5
1.5	$30	$22	$16
3.0	$42	$36	$31
6.0	$78	$65	$57

All Production From One Property.

FIGURE 15

PROBABILITY MODEL FOR GOLD DISCOVERY

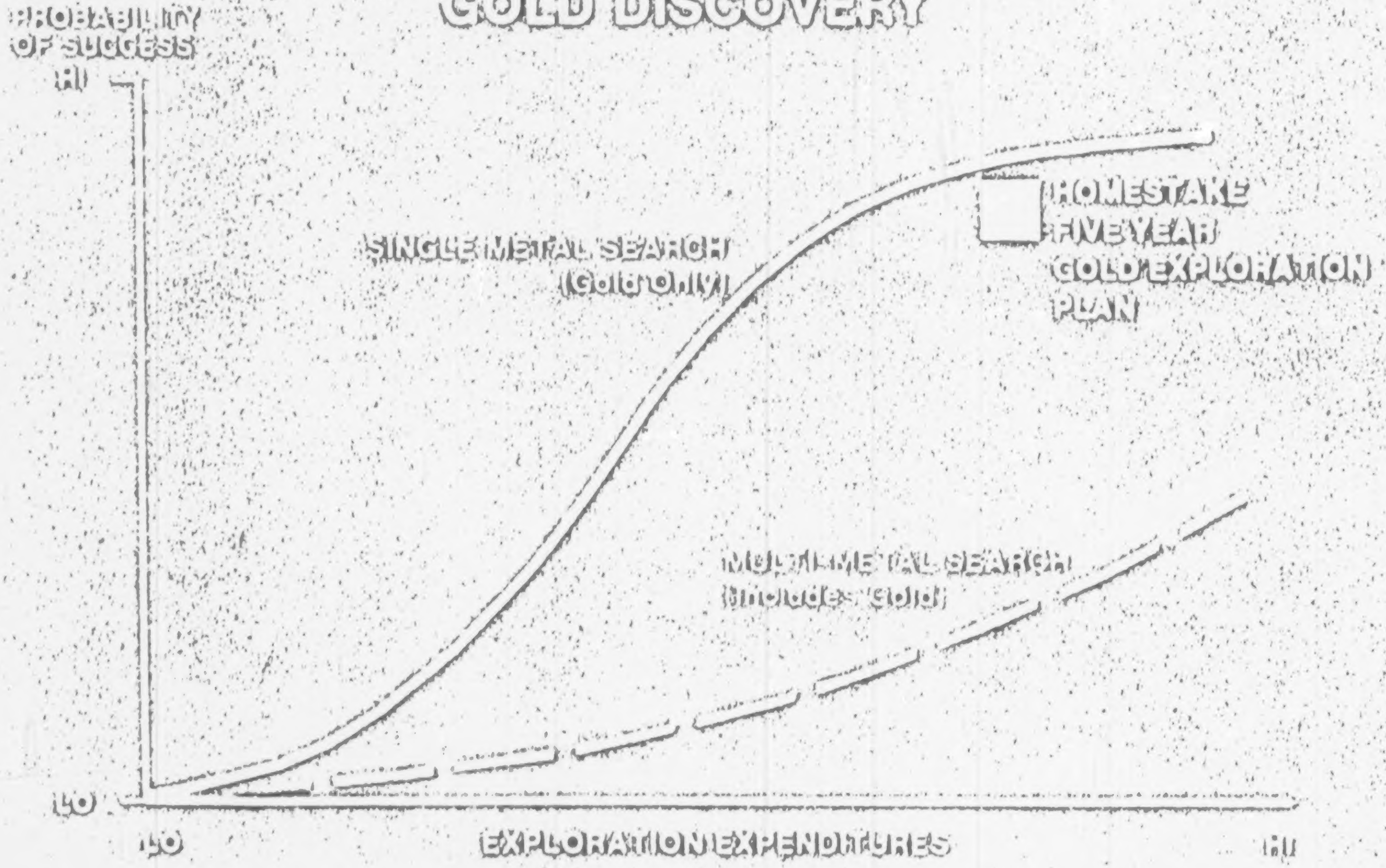


FIGURE 15

GOLD EXPLORATION BUDGET

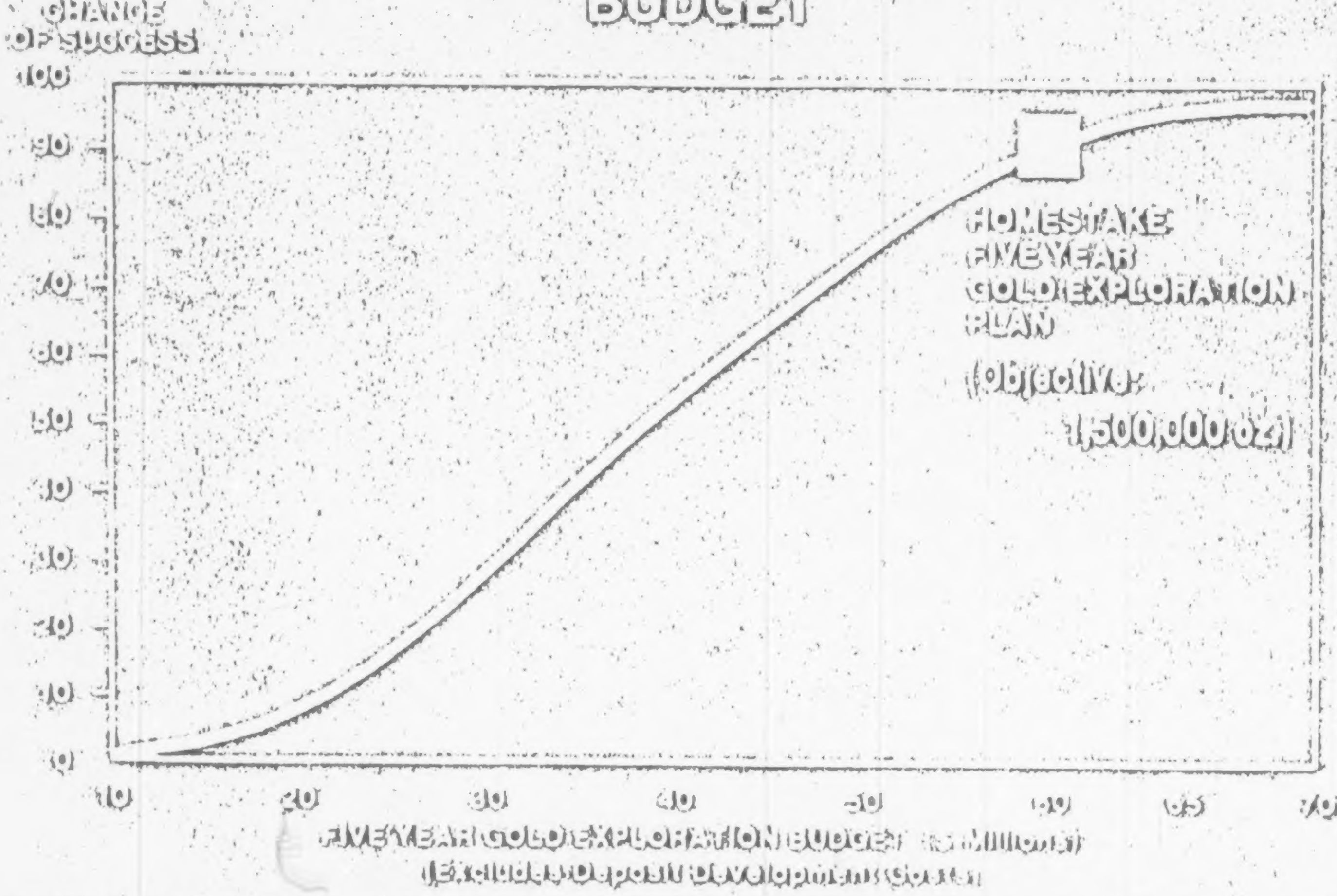


FIGURE 17

EXPLORATION PROBABILITY STATISTICS—U.S. GOLD PROGRAM

	Number of Projects Strategic Objectives	
	5-year plan	10-year plan
Reconnaissance		
• Reconnaissance Exams	2000	4000
• Detailed Evaluations	200	400
Target Exploration		
• Target Evaluations	65	130
• Ore Target Evaluations	16	32
Resource Development		
• Deposit Inventory	8	16
• Deposit Development	4	8
Mine Discoveries		
• Economic (0.5 million oz.)	3	5
• Substantial (1.5 million oz.)	1	2
• Major (3 million oz.)	0	1

Exploration Expenditures
- 5-year plan: $60 million

± 20/oz =

FIGURE 18

ESTIMATED GOLD EXPENDITURE AND INCOME - FIVE YEAR PLAN

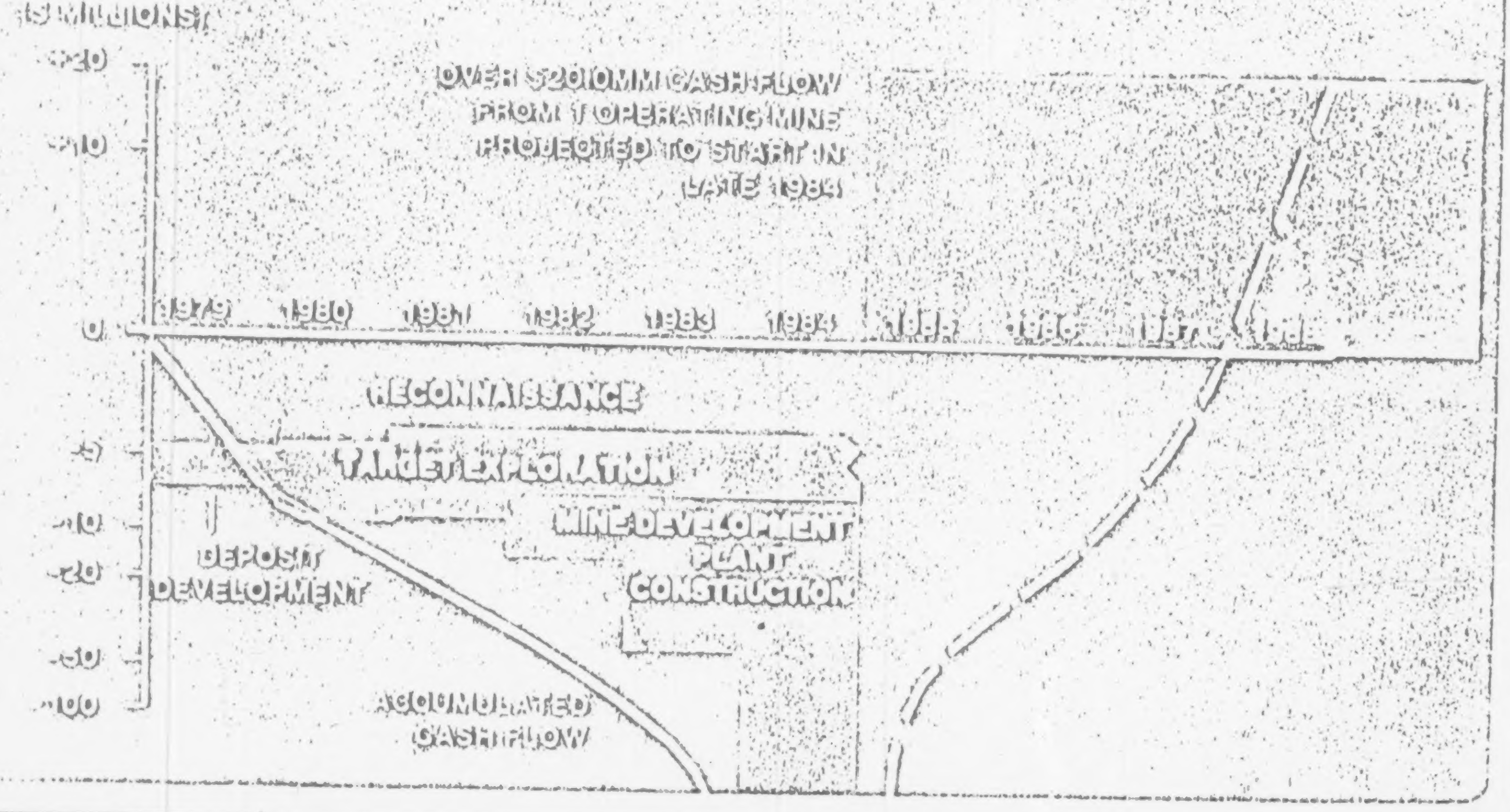


FIGURE 19

FUNCTIONAL
MANAGEMENT ORGANIZATION

Reconnaissance

Target Exploration

Deposit Development

Land Acquisition and Administration

FIGURE 20

APPLIED GEOLOGICAL RESEARCH

a. Refine geologic models/search areas with potential for known types of gold deposits.

b. Develop geologic models/search areas for poorly known or poorly understood gold deposits.

c. Develop theoretical concepts and techniques to search for new types of gold deposits.

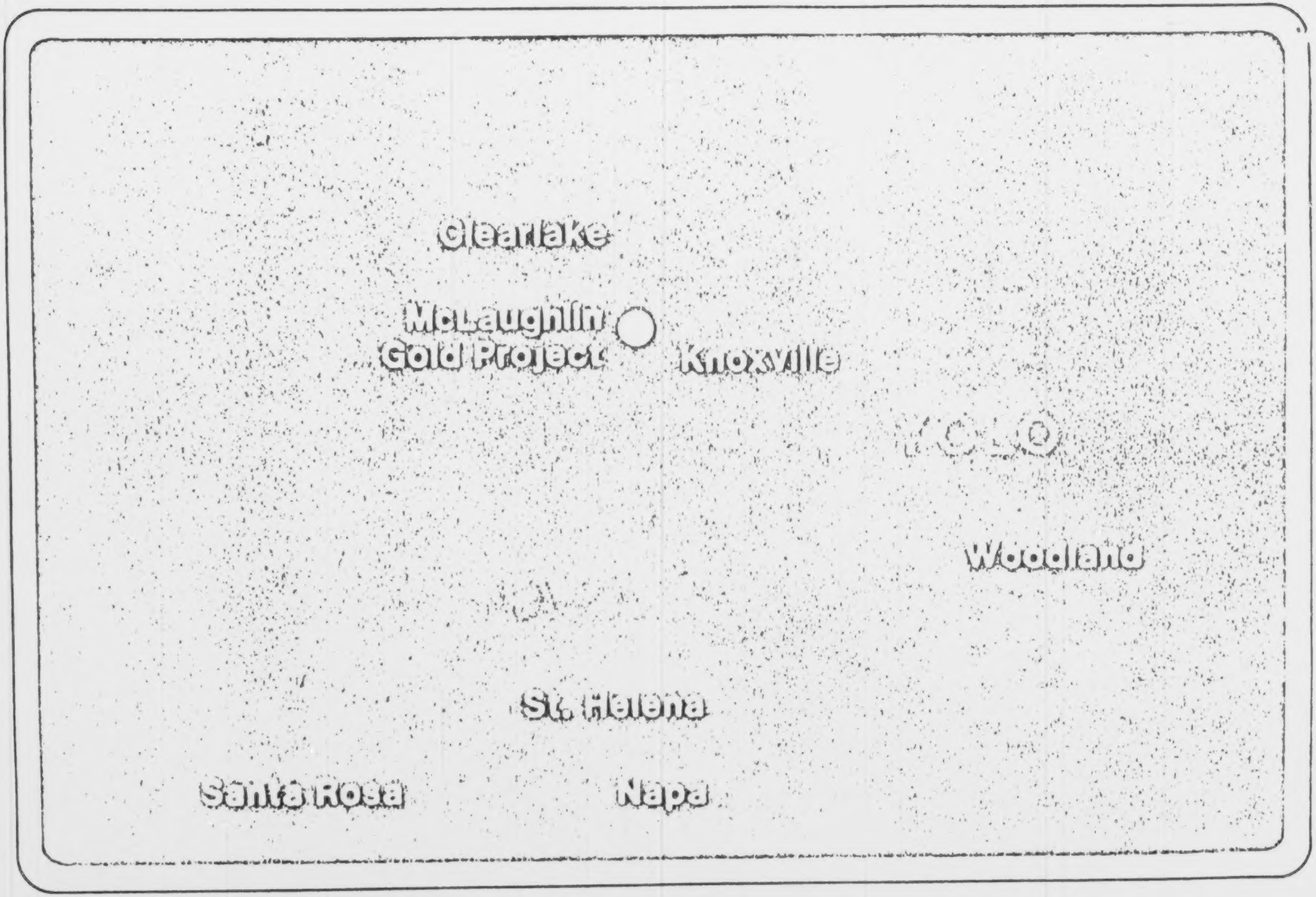
d. Improve performance and decision making at each functional stage of exploration.

FIGURE 21

EXPLORATION STATISTICS —U.S. GOLD PROGRAM

	Number of Projects 1979–1981 Program	
	Plan to Date	Results to Date
Reconnaissance		
• Reconnaissance Exams	1011	1111
• Detailed Evaluations	58	55 (4.95%)
Target Exploration		
• Target Evaluations	17	14 (25%)
• Ore Target Evaluations	2	3 (21%)
Resource Development		
• Deposit Inventory	3	3
• Deposit Development	0	0
Mine Discoveries		
• Economic (0.5 million oz.)	0	0
• Substantial (1.5 million oz.)	0	0
• Major (3 million oz.)	0	1 (0.09%) of Start

Exploration Expenditures to Date (2.5 years): $28 million


Clearlake
McLaughlin
Gold Project
Knoxville
YOLO
Woodland
St. Helena
Santa Rosa
Napa

List of Experts Interviewed

(*) interviewed in depth
others contacted on specific points

Dr. James A. Anderson (*)
Vice President - Exploration
Homestake Mining Company
San Francisco, California

Dr. Russell C. Babcock
Vice President
Bear Creek Mining Company
Anchorage, Alaska

Dr. G. Arthur Barber (*)
Vice President
Anaconda Minerals
Denver, Colorado

Robert G. Blair
Project Geologist
Getty Oil Company
Salt Lake City, Utah

Maurice H. Brady (*)
Vice President
Brooks Minerals
Lakewood, Colorado

Dr. Arthur A. Brant (*)
retired Chief Geophysicist
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Tucson, Arizona

Fred H. Brooks (*)
President
Brooks Minerals
Lakewood, Colorado

William H. Callahan
retired Exploration Manager
New Jersey Zinc Company
Franklin, New Jersey

Dr. Wayne S. Cavender (*)
retired Vice President - Exploration
Gulf Mineral Resources Company
Lakewood, Colorado

Dr. Clinton W. Dahlstrom (*)
Vice President

Chevron Resources Company
San Francisco, California

Dr. William M. Dolan
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AMAX Exploration
Golden, Colorado

Charles L. Elliot (*)
Elliot Geophysical Company
Tucson, Arizona

Walter E. Heinrichs (*)
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Dr. Willem Lodder (*)
Vice President
AMAX Exploration
Golden, Colorado

Hugh J. Matheson
President
Coca Mines, Inc.
Denver, Colorado

Tom Melrose
Vice President
UNC Teton Exploration
Casper, Wyoming

P. A. Meyer
ex Chief Geologist
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Broomfield, Colorado

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Frank W. Millsaps
Vice President - Metallurgy

Industrial Design Corporation
Salt Lake City, Utah

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Minerals Exploration Manager
Getty Oil Company
Los Angeles, California

Dr. Andrew E. Nevin
President
Granada Exploration Company
Nevada City, California

Dr. E.L. Ohle
retired Vice President
Hanna Mining Company
(Past President of Society of Economic
Geologists)
Salt Lake City, Utah

Dr. William C. Peters (*)
Consulting Geologist
Behre, Dolbear and Company
Tucson, Arizona

Dr. Edwin Post
President
Skyline Labs, Inc.
Wheat Ridge, Colorado

Jack Powers
Drilling Consultant
(formerly Vice President
E.J. Longyear Drilling Company)
Bloomington, Minnesota

Dr. G. G. Snow (*)
President
Noranda Exploration
Lakewood, Colorado

Robert S. Shoemaker (*)
(retired Vice President
Bechtel Corporation)
San Francisco Mining Associates
San Francisco, California

A. Percy Wicklund
Manager, Drilling Operations
AMAX Exploration
Golden, Colorado

Joseph E. Worthington (*)

Regional Manager
Rocky Mountain/Northern Region
Houston International Minerals
Lakewood, Colorado

Appendix F

Lists of World Class Deposits
discovered in past 30 years

from

EXPLORATION OR AQUISITION - THE OPTIONS
FOR ACQUIRING VIABLE MINERAL DEPOSITS

by Douglas R. Cook

(Presented at the American Mining Congress,
San Francisco, September, 1983)

WORLD CLASS METAL DEPOSITS DISCOVERED IN AFRICA DURING THE LAST 30 YEARS

DISCOVERY TYPE*	DEPOSIT AND LOCATION	METALS	STATUS**
E	ARLITT DISTRICT, NIGER	U	O
E	BLACK MOUNTAIN, SOUTH AFRICA	Pb, Zn, Cu	O
E	GAMSBURG, SOUTH AFRICA	Zn	O
A	MUSOSHI, ZAIRE	Cu	O
E	PALABORA, SOUTH AFRICA	Cu	O
E	PIKWE-SELEBI, BOTSWANA	Cu, Ni	O
E	PRIESKA, SOUTH AFRICA	Cu, Zn	O
E	ROSSING, NAMIBIA	U	O

EXPLORATION - 7 (88%)

ACQUISITION - 1 (12%)

* HOW OBTAINED BY PRESENT OWNER: E = EXPLORATION

A = ACQUISITION

** PRESENT STATUS: O = OPERATING

D = DEVELOPMENT

P = PRE-DEVELOPMENT

WORLD CLASS METAL DEPOSITS DISCOVERED IN OTHER NON-COMMUNIST COUNTRIES DURING THE LAST 30 YEARS

DISCOVERY TYPE*	DEPOSIT AND LOCATION	METALS	STATUS**
E	ERTSBERG-ERTSBERG EAST, INDONESIA	Cu, Au	O
E	MARCOPPER, PHILIPPINES	Cu	O
E	NAVAN, IRELAND	Zn, Pb	O
A	OK TEDI, PAPUA NEW GUINEA	Cu, Au	D
E	PANGUNA, PAPUA NEW GUINEA	Cu, Au	O
N	SAR CHESHMEH, IRAN	Cu	O

EXPLORATION - 4 (66%)
ACQUISITION - 1 (17%)
NATIONALIZED - 1 (17%)

* HOW OBTAINED BY PRESENT OWNER: E = EXPLORATION
A = ACQUISITION
N = NATIONALIZED

** PRESENT STATUS: O = OPERATING
D = DEVELOPMENT
P = PRE-DEVELOPMENT

WORLD CLASS METAL DEPOSITS DISCOVERED IN AUSTRALIA DURING THE LAST 30 YEARS

DISCOVERY TYPE*	DEPOSIT AND LOCATION	METALS	STATUS*
E	ELURA, SOUTH AUSTRALIA	Pb, Zn, Ag	O
E	HILTON, QUEENSLAND	Pb, Zn, Ag	P
E	JABILUKA, NORTHERN TERRITORY	U	D
E	KAMBALDA, WESTERN AUSTRALIA	Ni	O
E	RANGER, NORTHERN TERRITORY	U	O
E	ROXBY DOWNS, SOUTH AUSTRALIA	Cu, U	P
E	TELFER, WESTERN AUSTRALIA	Au	O
E	WOODLAWN, NEW SOUTH WALES	Zn, Cu, Pb, Ag	O

EXPLORATION - 8 (100%)

* HOW OBTAINED BY PRESENT OWNER: E = EXPLORATION

** PRESENT STATUS: O = OPERATING
D = DEVELOPMENT
P = PRE-DEVELOPMENT

WORLD CLASS METAL DEPOSITS DISCOVERED IN LATIN AMERICA DURING THE LAST 30 YEARS

DISCOVERY TYPE*	DEPOSIT AND LOCATION	METALS	STATUS**
N	ANDINA, CHILE	Cu, Mo	O
A	CERRO COLORADO, PANAMA	Cu, Mo	P
E	CUAJONE, PERU	Cu	O
E	EL INDIO, CHILE	Au	O
N	EL SALVADOR, CHILE	Cu	O
A	EL SOLDADO, CHILE	Cu	O
N	EXOTICA, CHILE	Cu	O
A	LA CARIDAD, MEXICO	Cu	O
E	LA ESCONDIDA, CHILE	Cu	P
A	LOS BRONCES, CHILE	Cu, Mo	P
N	PUEBLO VIEJO, DOMINICAN REPUBLIC	Au	O
E	QUEBRADA BLANCA, CHILE	Cu, Mo	P

EXPLORATION - 4 (33.3%)
ACQUISITION - 4 (33.3%)
NATIONALIZED - 4 (33.3%)

* HOW OBTAINED BY PRESENT OWNER: E = EXPLORATION
A = ACQUISITION
N = NATIONALIZED

** PRESENT STATUS: O = OPERATING
D = DEVELOPMENT
P = PRE-DEVELOPMENT

WORLD CLASS METAL DEPOSITS DISCOVERED IN CANADA DURING THE LAST 30 YEARS

DISCOVERY TYPE*	DEPOSIT AND LOCATION	METALS	STATUS**
A	AFTON, BRITISH COLUMBIA	Cu	0
A	ANVIL-GRUM, YUKON	Pb, Zn, Ag	0
E	ATHABASKA DISTRICT, SASKATCHEWAN	U	P
A	BETHLEHEM, BRITISH COLUMBIA	Cu, Mo	0
E	BLIND RIVER, ONTARIO	U	0
E	ENDAKO, BRITISH COLUMBIA	Mo	0
E	GASPE, QUEBEC	Cu	0
E	HEMLO, ONTARIO	Au	D
A	KIDD CREEK, ONTARIO	Zn, Ag, Cu	0
A	LORNEX, BRITISH COLUMBIA	Cu, Mo	0
A	MATTAGAMI, QUEBEC	Cu, Pb, Zn, Ag	0
E	PINE POINT, NORTHWEST TERRITORIES	Pb	0
E	RUTTAN LAKE, MANITOBA	Cu, Zn	0
E	THOMPSON, MANITOBA	Ni	0

EXPLORATION - 8 (57%)
ACQUISITION - 6 (43%)

* HOW OBTAINED BY PRESENT OWNER: E = EXPLORATION
A = ACQUISITION

** PRESENT STATUS: O = OPERATING
D = DEVELOPMENT
P = PRE-DEVELOPMENT

WORLD CLASS METAL DEPOSITS DISCOVERED IN THE U.S.A. DURING THE LAST 30 YEARS

DISCOVERY TYPE*	DEPOSIT AND LOCATION	METALS	STATUS**
A	AMBROSIA LAKE, NEW MEXICO	U	O
E	ARCTIC, ALASKA	Cu, Zn, Pb, Ag	P
E	BIXBY, MISSOURI	Pb, Zn, Cu	O
E	BURGIN-TRIXIE, UTAH	Ag, Au, Pb, Zn	D
E	CARLIN, NEVADA	Au	O
E	CRANDON, WISCONSIN	Au, Cu	P
E	EMINENCE, MISSOURI	Pb, Zn	O
E	HENDERSON, COLORADO	Mo	O
E	JERRITT, NEVADA	Au	O
A	KALAMAZOO, ARIZONA	Cu, Mo	D
E	MAGMONT, MISSOURI	Pb, Zn	O
E	McLAUGHLIN, CALIFORNIA	Au	D
E	METCALF, ARIZONA	Cu	O
E	MINERAL PARK, ARIZONA	Cu, Mo	O
E	MISSION, ARIZONA	Cu	O
E	MT. EMMONS, COLORADO	Mo	P
E	OZARK, MISSOURI	Pb	O
A	PIMA, ARIZONA	Cu	O
E	RED DOG, ALASKA	Zn	P
A	TROY, MONTANA	Cu, Ag	O
E	VIBURNUM, MISSOURI	Pb, Zn	O
E	WENATCHEE, WASHINGTON	Au	D

EXPLORATION - 18 (82%)

ACQUISITION - 4 (18%)

* HOW OBTAINED BY PRESENT OWNER: E = EXPLORATION
A = ACQUISITION

** PRESENT STATUS: O = OPERATING
D = DEVELOPMENT
P = PRE-DEVELOPMENT

Exploration for Strategic Materials

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Conclusions	C 1 - 25
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Cobalt	S 7 - 13
Manganese	S 13 - 17
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